DEVELOPMENT OF A RAPID CURRENT CONTAINMENT BOOM:

PHASE III

TECHNICAL REPORT

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1. INTRODUCTION

Purpose

Historically conventional oil booms have been essential tools in oil spill clean up efforts. However, in environments where currents are present booms have always had difficulty containing oil. If the perpendicular component of the relative current speed exceeds a critical value, the oil boom fails. This critical value has been found to be between 0.6 and 1.0 knots, depending on the oil's properties. This poses a serious problem since tidal currents exceed this critical value in many major harbors and ports where bulk oil is handled.

In addition, any efforts to use conventional oil boom in sweep configurations, or as a skimmer, are limited by the necessity for low relative current speeds. This creates difficulties for boat operators who may find their vessels' maneuverability hindered at speeds of less than one knot. Finally, it is important to contain oil as quickly as possible after a spill to prevent dispersion and to limit environmental damage. This effort is greatly hampered by slow vessel operating speeds.

The main purpose of this work was to develop a new type of flexible oil barrier which could collect oil in currents at speeds at least twice that of conventional oil boom. It was intended that this barrier would solve many of the problems mentioned above. In the effort described here, the principal goal was to develop, fabricate and test a full-scale, full-width, rapid current containment barrier prototype. Activities pertaining to the flexible barrier portion of this study have also been described by Steen (1997).

A second goal was to conduct an experimental program involving standard, vertical oil booms to generate data for comparison with numerical model predictions of conventional oil boom failure. Observations of oil loss mechanisms were obtained and shared with investigators from the University of Rhode Island (URI). The URI team has been developing computer simulations in a companion study and required oil slick test data for calibration and evaluation.

Previous Work

This report summarizes the third-year effort in a program to develop fast current oil barriers based upon the submergence plane concept. Prior to efforts reported here, the two-dimensional submergence plane cross section shown in Figure 1 was demonstrated to be very effective at collecting oils in flume experiments at speeds of up to three times the critical speed of conventional oil boom (Swift et al. 1995, 1996a and Coyne, 1995). It was then shown by Swift et al. (1996b) that this two-dimensional cross section could be converted into very basic, semi-rigid, free-floating, three-dimensional modules (see Figure 2). These modules were tested in the Great Bay estuary, NH at the apex of two pieces of conventional oil boom as in Figure 3. The results of these tests were very promising and led to the next stage of development.

It was always the intention of this study to create a flexible oil barrier. With the success of the semi-rigid modules, efforts began to introduce flexibility into this basic design. The first attempt was the full longitudinal representative segment (see Figure 4) (Swift et al., 1996b). This device was intended to represent a segment of a full-width device which was to be built later on in

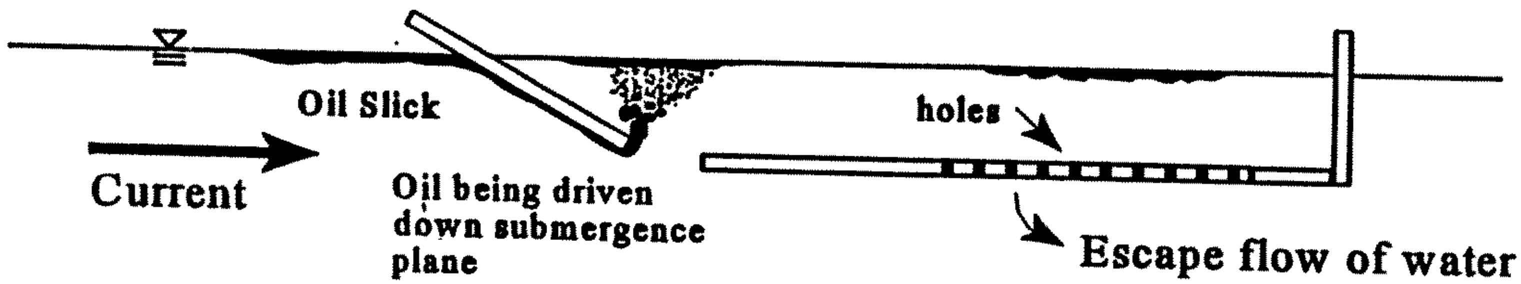
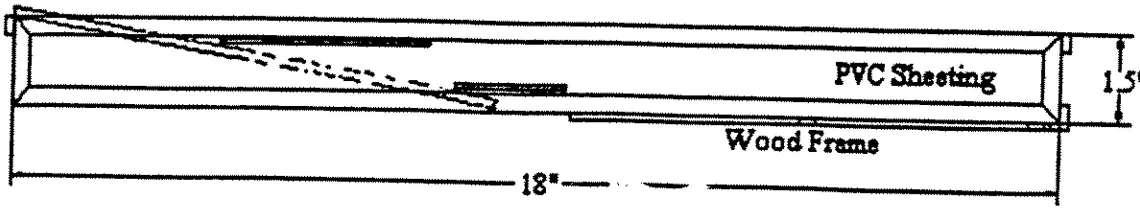
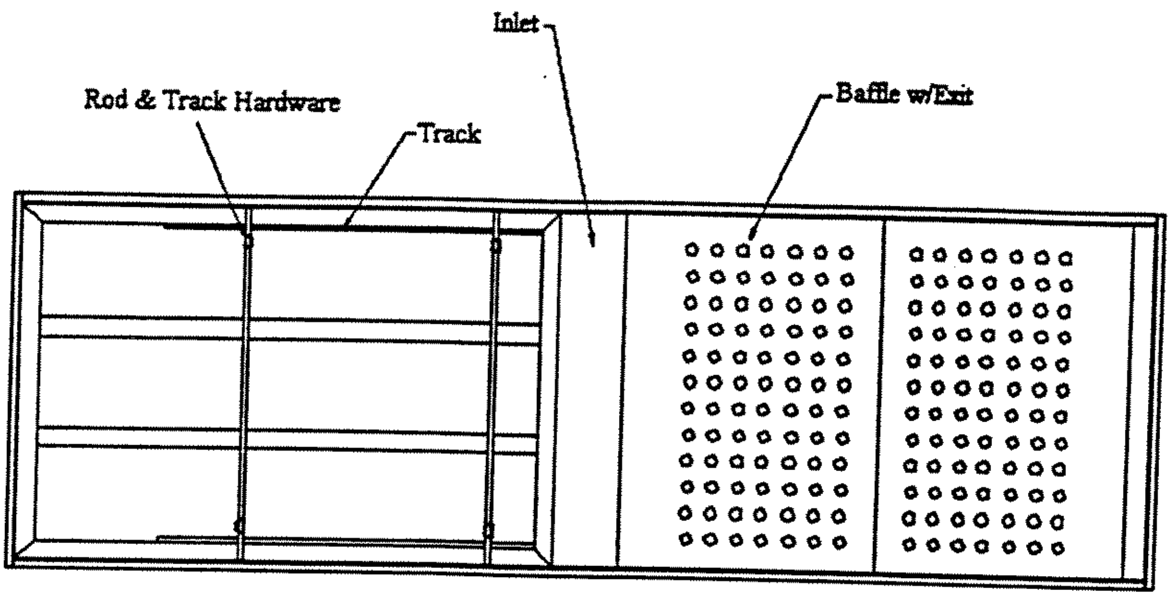


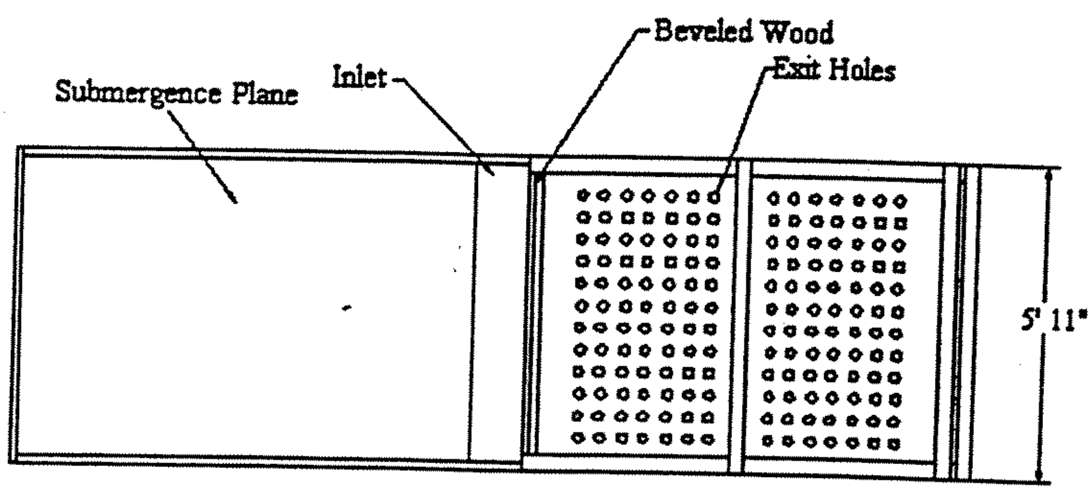
Figure 1 Cross-section of the submergence plane barrier.



Schematic side view of Prototype. Wood frame and PVC sheeting are labeled.



Schematic top view of Prototype. Major components are labeled.



Schematic bottom view of Prototype. Major components are labeled.

Figure 2 Schematic of a semi-rigid module.

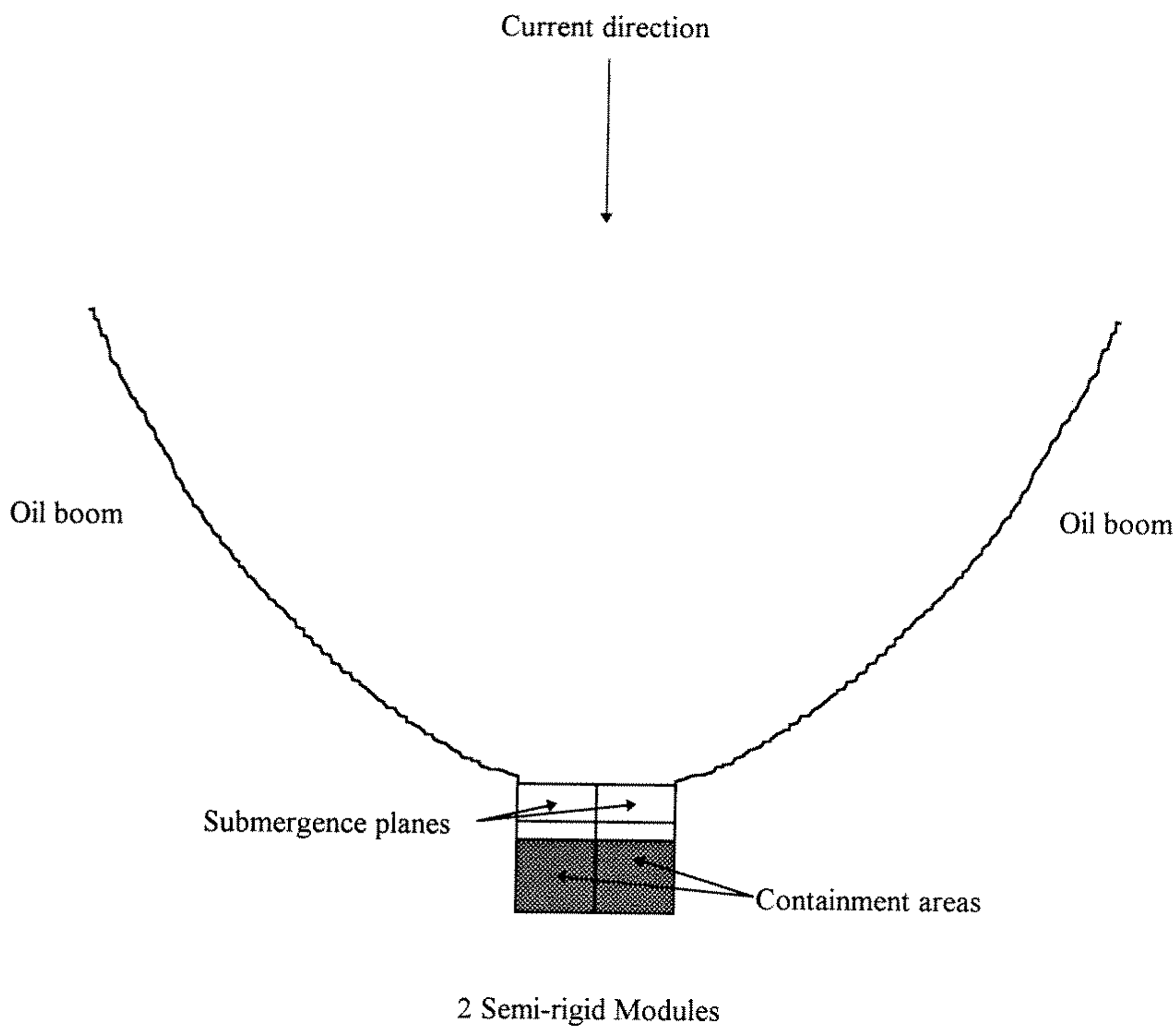


Figure 3 Deployed semi-rigid modules.

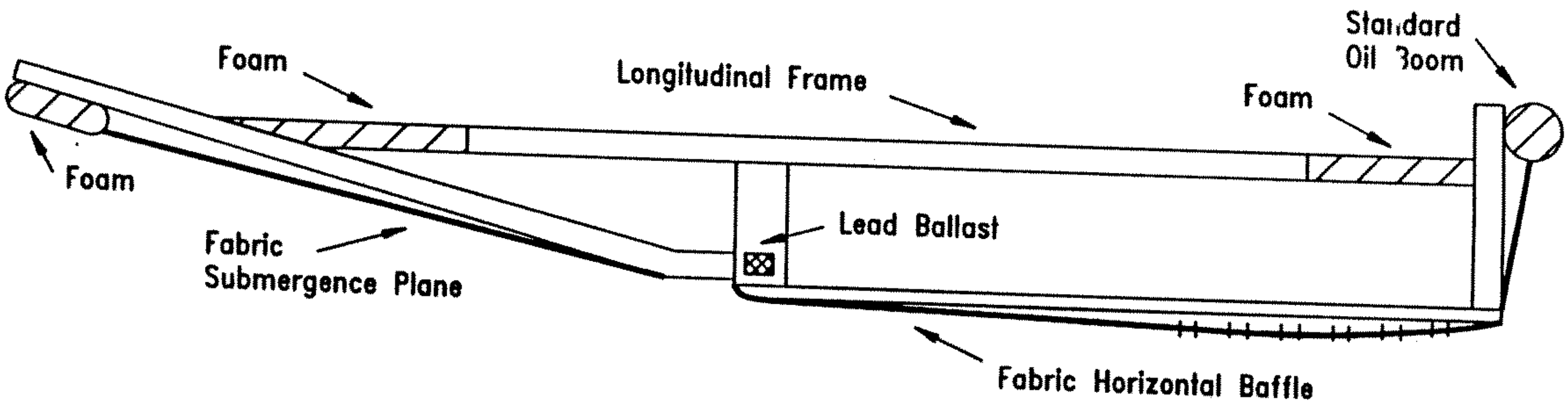


Figure 4 Cross-section of the full longitudinal representative segment.

the development program. Field tests were also conducted with this device in the Great Bay estuary, NH. Results were very promising and proved that flexibility was indeed possible in these systems.

Some questions had arisen from these first two attempts at a three-dimensional system. The first question dealt with the draft of these devices. Due to depth limitations of the flume used in the initial work, it was not possible to discover if there was an ideal draft for these systems. Questions remained about how much draft could be designed into these systems. Another question arose regarding the full longitudinal representative segment. During the field tests it had become apparent that this system was awkward, at best, to work with and transport. It was also obvious that the length of the longitudinals would limit the size of the containment area of these systems. It became apparent that improvements could be made to this design.

In a research effort at URI, carried out at the same time, fluid dynamic numerical models had been developed to predict failure mechanisms of standard, single vertical barrier oil booms. The purpose was to understand the limits of this technology which is now the backbone of the oil spill response arsenal. The two-dimensional computer simulations that had been developed by Grilli et al. (1996,1997) clearly showed the expected failure modes, but there had been no direct validation with experiment. The University of New Hampshire (UNH) laboratory flume facility was ideally suited to meet this need.

Objectives

The specific goals may be grouped into two categories - development of submergence plane technology and the experimental investigation of standard boom failure modes. The major objectives, organized in this manner are:

High speed current barrier development

1. Improve upon the performance of the initial three-dimensional designs
2. Develop a full-width flexible oil barrier based upon these improvements
3. Begin to introduce manufacturing, logistics, transportation, deployment, recovery, and storage issues into the design of the full width system
4. Evaluate designs in tests using real oils.

Standard oil boom testing

1. Conduct flume tests corresponding to two-dimensional, URI numerical model experiments
2. Record slick shape digitally and share observations with URI collaborators.

Approach

The fundamental approach used in developing the flexible barrier was experimental - a logical sequence of tests were carried out to answer specific performance and design questions. The tests utilized scale models and full scale representative segments with exploratory experiments conducted at the Jere Chase Ocean Engineering Laboratory Tow Tank at UNH. The results of these tests were used to develop a full-width, experimental prototype for evaluation at The National Oil Spill Response Test Facility (hereafter referred to as Ohmsett).

Specifically, initial efforts focused upon improving the designs and performance of the previously developed three-dimensional systems. These efforts began with an attempt to answer the draft question. A series of retention experiments were devised which utilized a rebuilt, semi-rigid module. They were conducted in the UNH tow tank with oil substitutes. Results from these tests can be found in the next section.

With the completion of these tests, work began to consider a design alternative to the full length longitudinal representative segment. From this work a short longitudinal representative segment was designed, built and tested in the UNH tow tank (using oil substitutes).

There were then two successful, flexible system designs available, one of which would be expanded into a full-width system. To help select the best design for expansion, it was decided to test the systems at Ohmsett, as described in Section 3, where they could be subjected to real oil. The discussion on which design concept to use for the full-width barrier prototype was also based on logistical considerations and ease of manufacturing

Employing the selected concept, a full-width prototype barrier was designed and built. The design rational, scale model testing, and the as-built system are described in Section 4. It, too, was taken to Ohmsett to be tested. The results of these tests can be found in Section 5.

In the collaborative work with URI, plane vertical barriers were used to represent standard oil boom in experiments carried out in the UNH recirculating flume. The flume is dedicated to oil spill response research using real oils. The flume is 40 feet long, four feet wide, and four feet deep, and it is driven by two variable speed electric motors connected to counter-rotating propellers. The test section is walled by clear acrylic panels allowing visual observations and access by optical instrumentation. During the experiments the slick profile was recorded using high resolution video with output directly to a computer, 35mm still photography, and standard video. Test methods and results are summarized in Section 6.

2. DEVELOPMENT OF THE FLEXIBLE SYSTEM CROSS-SECTION

Draft

Efforts to improve the performance of the three-dimensional devices began with the draft issue. As has been stated, the effect of draft on these systems was never fully explored due to the depth limitations of the flume. It was thought that a deeper draft would be beneficial, but no experiments had been done to confirm this belief.

In theory, a deeper draft would help improve containment in two ways. First, a deeper draft would necessitate a longer submergence plane (i.e. if the plane remains at a constant angle, a device with a 15 inch draft would have a longer plane than a nine inch draft). As such, as the oil traveled down the plane it would get farther from the turbulence on the surface of the water, and it would become more concentrated. This, in turn, improved the chances that the oil would enter the gap at the bottom of the submergence plane. The second way that a deeper draft would help is by creating greater separation between the oil on the surface in the containment area and the exit holes which the water escapes out of. It was felt this would limit the amount of oil entrainment, the oil lost with the escaping water. But, all of this was theory; it needed to be determined whether an increase in draft was going to be beneficial .

The tests were conducted in the UNH tow/wave tank. The tank is 120 feet long, 12 feet wide, and eight feet deep. It has a substantial tow carriage which is designed to operate at up to five knots while towing oil collection systems. The carriage is a cable driven, dominant siderail, system. It is driven by a 10 hp. three-phase AC motor which is controlled by a Baldor frequency inverter.

To perform these tests a single semi-rigid module was rebuilt to accommodate an increase in draft. It was then suspended beneath the carriage using one of two sets of four tie lines. One set held the device at a draft of eight and one quarter inches, and the other set held it at 19.5 inches. The draft tests were conducted at two different speeds, two and four tenths knots and one and a half knots. Small one eighth inch beads, with a specific gravity of 0.93, were used to simulate the oil slick. These beads were used because they mimicked small oil droplets quite well. The beads were distributed by hand from a one foot wide hopper, centered on the tank, which was kept ten feet in front of the device as it moved down the tank.

Some problems arose in these tests due to the length of the semi-rigid module compared to that of the tow tank. It took almost half the length of the tank for the device to come to a steady state condition, which was necessary for the introduction of beads. As a result, there was not much tank length left in which to collect a slick, and decelerate the device. The problem was dealt with by skipping the deceleration process. The device was run almost to the end of the tank and then stopped. This did cause bead washout which made quantifying the captured beads very difficult. To solve this problem an oil boom was suspended above the tank just before the point where the device would be stopped. Then, during a run, when the device passed under the boom, the boom would be dropped into the tank, effectively trapping all the beads that washed out between the boom and the end of the tank. Beads that were in this region were considered captured; beads that were between the boom and the far end of the tank were considered lost.

These experiments were done for comparison purposes only. The results are in Table 1. As can be seen, at the faster speeds a deeper draft did improve the performance of the device. At slower speeds the results were less conclusive, but did show that an increase in draft was, at the very least, not detrimental to performance. As a result, it was concluded that a deeper draft would normally improve a design's performance.

Short Longitudinal Concept

With the draft question answered, it was time to address the short-comings of the initial flexible, three-dimensional design. The longitudinal length of full longitudinal representative segment, shown in Figure 4, was found to make the device awkward, and limited the size of the containment area. The most obvious solution to these problems was to develop a short longitudinal representative segment (Figure 5). It was felt that the benefits of this system would be the following;

- It would be much easier to build/assemble
- It would be much easier to transport
- It would be possible to have a larger containment area.

Table 1 Results of draft tests.

Test #	Test Speed (kts)	Draft (in)	Vol. Beads Introduced (ml)	Vol. Captured (ml)	% Lost
1	2.4	8.25	4000	3100	22.50
2	2.4	8.25	4000	3150	21.25
3	2.4	8.25	4000	3175	20.63
4	2.4	19.5	4000	3900	2.50
5	2.4	19.5	4000	3550	11.25
6	2.4	19.5	4000	3600	10.00
7	1.5	19.5	4000	3840	4.00
8	1.5	19.5	4000	3750	6.25
9	1.5	8.25	4000	3825	4.38
10	1.5	8.25	4000	3600	10.00

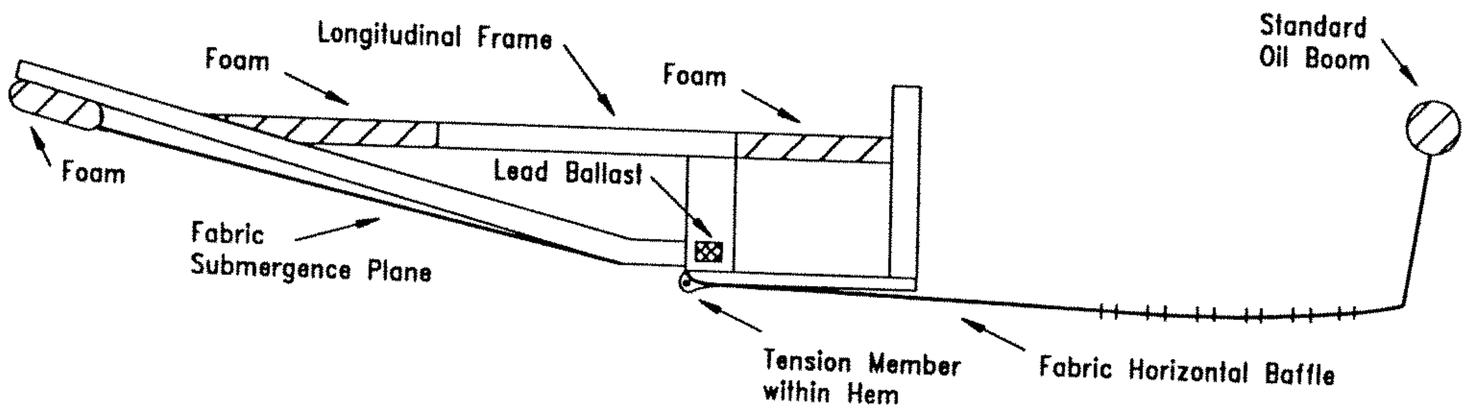


Figure 5 Cross-section of the short longitudinal representative segment.

The big question remaining was, would the drag forces be enough to maintain the shape of the containment area of the device? To answer this question a short longitudinal representative segment was designed, built, and tested in the UNH tow tank. Like the full longitudinal representative segment, it was conceived to be a segment of a full-width device.

The device was designed to utilize material provided by Mr. J. Santamaria of JPS/OILTROL Inc.. It was approximately 12.85 feet long, five and three quarters feet wide and had a nine inch draft. Initially tow tests of the device showed that it would maintain shape, but that water would flow over the sides of the containment area at moderate speeds. Buoyancy and freeboard were added to the sides of the containment area which solved the problem.

Bead tests utilized the same beads and distribution system as the draft tests. The device was attached to the carriage by two vertical posts with pulleys on their lower end (see Figure 6). Lines were attached at each side of the device, run through the pulley, and then up the post to the carriage. These lines enabled tension to be applied in the cross current direction to the device to simulate the mooring load of a full-width device. The tests were conducted at one and a half knots. The results were 100 percent retention of the beads. Thus, the short longitudinal representative segment was considered a very viable design alternative.

Upgrading the Representative Segments

With the excellent results of the short longitudinal segment tests, there were two promising, flexible design alternatives: the short longitudinal system and the full longitudinal

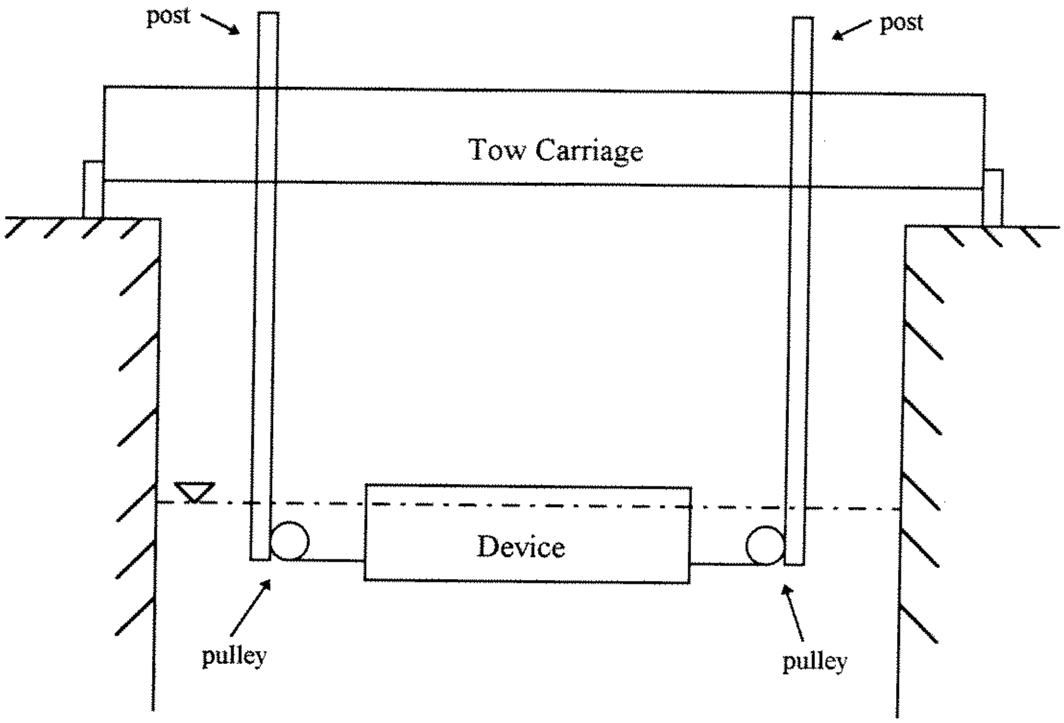


Figure 6a Front view

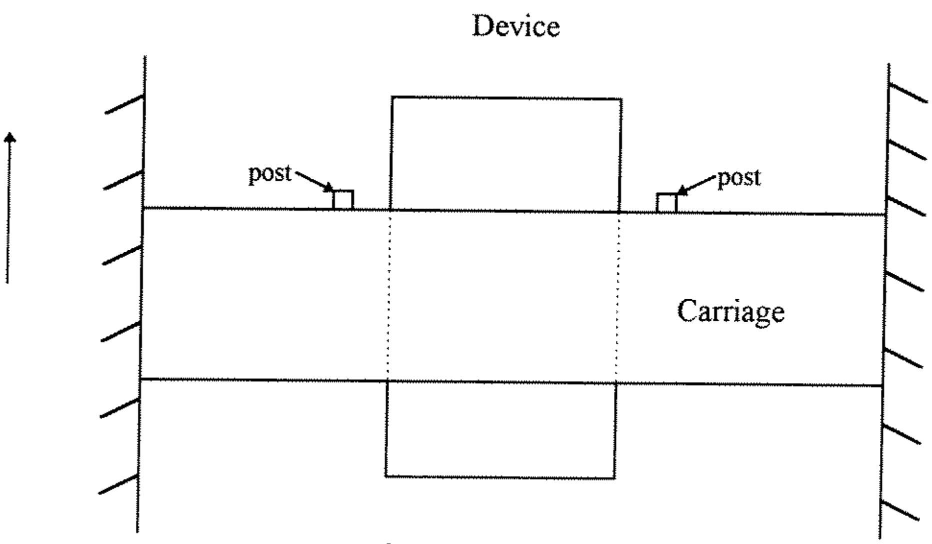


Figure 6b Plan view

Figure 6 Device attachment to carriage.

system. Though there was a general sense that the short longitudinal segment was a better design, further evaluation with real oils was necessary before this decision could be finalized. Since it was not possible to conduct oil tests in the UNH tow tanks, it was decided to take the devices to Ohmsett.

Before the devices could make this trip both of them needed to be rebuilt to generally increase their robustness and to reflect the lessons learned during the previous year of testing. The improvements in the short longitudinal system (Figure 7) included a still greater increase in the side buoyancy of the containment area, an increase in the buoyancy of the longitudinals, and an increase in freeboard. Finally, the original system had been built with wooden members, and a light plastic covered fabric. For the trip the wooden longitudinals were strengthened and the entire system was reskinned in standard oil boom fabric which was provided by JPS/OILTROL Inc..

The improvements to the full longitudinal system (Figure 8) included an increase in the buoyancy of the longitudinals, an increase in the submergence plane reserve buoyancy (i.e. the buoyancy at the top of the submergence plane, see Figure 4), an increase in freeboard, and reskinning in standard oil boom material which was again provided by JPS/OILTROL Inc.. Finally, the wire tension member (found at the leading edge of the horizontal baffle) was replaced with a chain during the rebuilding process.

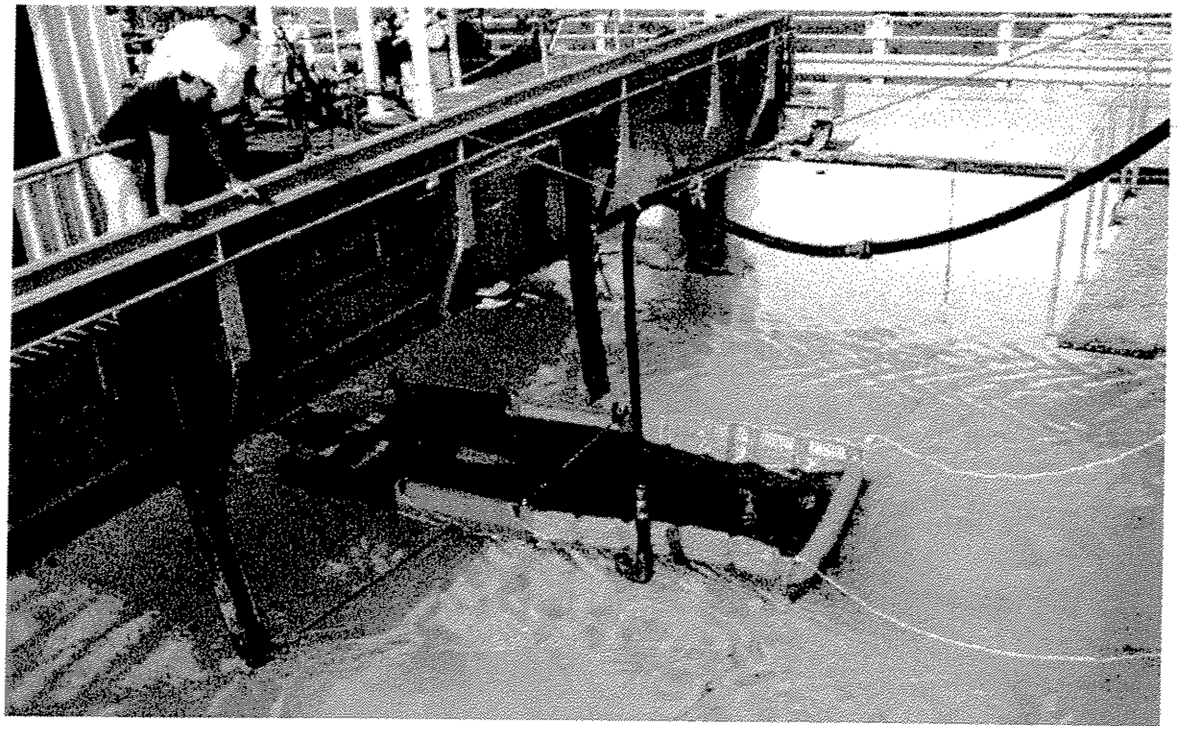


Figure 7 The short longitudinal representative segment.

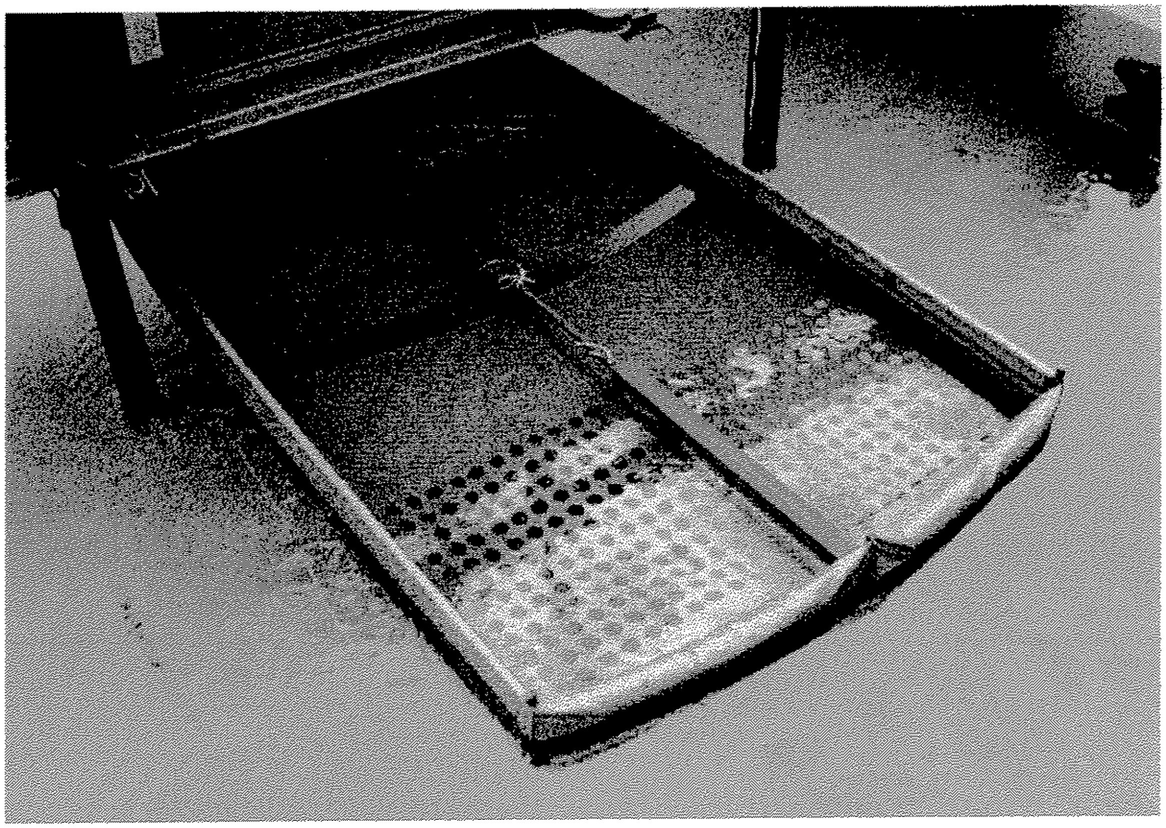


Figure 8 The full longitudinal representative segment.

3. REPRESENTATIVE SEGMENT TESTING AT OHMSETT

Test Objectives

This Ohmsett trip allowed for thorough evaluation of the short and full longitudinal representative cross-sections using real oils. In addition, it provided an opportunity to evaluate other aspects of these devices besides their retention ability. Of particular interest was a more thorough evaluation of their gap openings, exit areas, and flow plane angles. This was possible because the Ohmsett tank was seven time longer than the UNH tank and allowed for much longer test runs. In addition, this greater length provided an opportunity to take the devices to higher steady state speeds to evaluate strength considerations.

Ohmsett Configuration

The Ohmsett tow tank is a large outdoor tank which is configured to conduct tests with oil. It is 666 feet long, 65 feet wide, and 11 feet deep. It is filled with 9.84 million gallons of brackish water. There are three tow carriages on the tank which are referred to as bridges (see Figure 9). These bridges are independently connected to a common cable drive system on each side of the tank, and are capable of towing speeds of up to six and a half knots. It is possible to adjust the spacing between the bridges by adjusting where they connect to the drive cables. The first bridge is a small one which is equipped with fire hoses that are used to "corral" oil at the end of tests, or during cleaning. The second bridge is the main bridge which carries the oil distribution system, the controls for the two underwater cameras, and it is the primary platform from which to

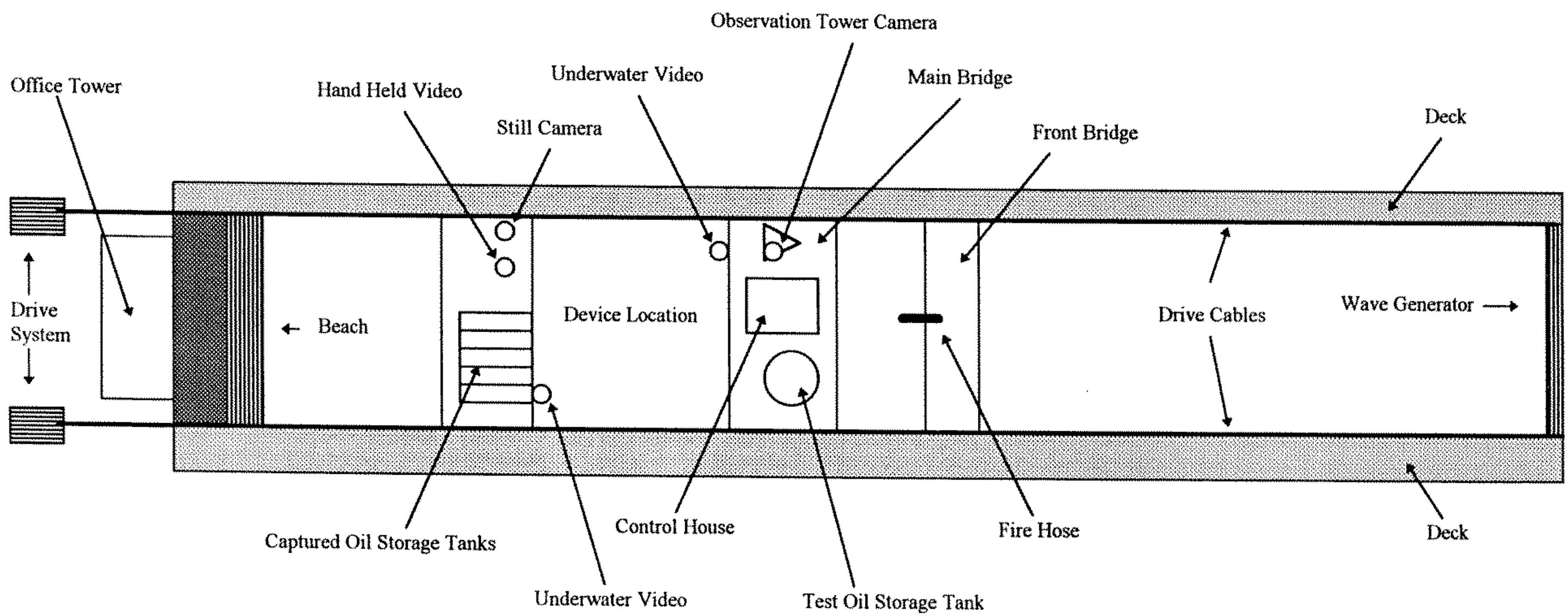


Figure 9 Ohmsett layout (not to scale).

view the tests. The final bridge is the auxiliary bridge which is equipped with the oil recovery system and holding tanks.

The tow tank also has a single flap wave generator which is capable of simulating regular waves of up to one meter in height. Regular waves are dissipated by a "beach" at the office tower end of the tank (where runs are initiated). Ohmsett is operated by the Minerals Management Service (MMS) through a contract with MAR Inc.

For these tests the devices were attached to the main tow bridge with two post down beams in much the same way as at UNH (see Figure 6). A come-along and chains were utilized to add the proper cross current tension to the devices. Tow lines were strung from the auxiliary bridge to the rear barrier of the device to help it maintain shape while on the return trip after a test. These lines were kept slack during test runs down the tank.

Measurement Methods and Test Protocol

The main quantifier of barrier performance is the percentage of oil encountered that is retained within the barrier, hereafter referred to as the Retention Percentage. It is found in the following way. At the conclusion of a test the captured oil is recovered and transferred to recovery tanks. Here the oil is given time to separate from the majority of the water which is recovered with it. This water is then decanted from the bottom of the tanks, and measurements of the remaining oil are made to determine the gross volume of the recovered oil. Before the oil is reprocessed, samples are taken and used for chemical analysis. This analysis reveals the percent of water that is still mixed with the oil, and the amount of "other material" in the oil. The amount of water and other material is subtracted from the gross volume, and the volume of oil recovered is left. Retention Percentage is just the volume of oil recovered divided by the volume of oil encountered (measured while distributing it) multiplied by 100. Retention Percentage for barriers actually corresponds to Throughput Efficiency for skimmers which is a common measurement for Ohmsett personnel.

The two oils commonly used at Ohmsett were employed in the representative segment tests. Sundex is their heavy, viscous test oil, while Hydrocal is used to represent the class of light, low viscosity oils. Their characteristics are listed below.

Oils	*Kinematic Viscosity (centistokes) @ 20°C*	*Specific Gravity*	*Interfacial Tension (dyne/cm)*	*Surface Tension (dynes/cm)*
Sundex	20,000.0	0.955	34.4	35.5
Hydrocal	190.0	0.897	25.9	33.6

Table 2. Ohmsett's oil properties

The test protocol was as follows. When everyone was set, the test director from the main bridge would have the bridges brought up to speed. The speeds used for these tests ranged from the speed at which standard oil boom fails (one knot), up through the barrier's projected failure speed (two and a half knots).

Once at a chosen speed the test director would call for oil release. Oil was pumped from a tank on the main bridge, down a pipe, and released at the water level approximately six feet in front of the device. When the bridges neared the end of the tank the flow of oil was stopped, and the bridge operator started to decelerate the bridges.

Deceleration was necessary to prevent sudden stops and oil "wash out" from inside the device. Fire hoses from the front bridge were also used for this purpose. As the device began to decelerate the fire hoses were directed at the front of the barriers to create a "wall of water" which would prevent "wash out" over the top of the submergence plane.

Due to the placement of available pumps at Ohmsett, the devices had to be towed back to the other end of the tank before they could be pumped out. To prevent oil loss during the tow back the previously mentioned rear tow lines were tensioned to help the device maintain shape. In addition, the fire hoses were used continuously to keep captured oil from washing out over the bow while moving backwards. A vertical barrier was dropped beneath the auxiliary bridge during (slow) backups to separate "lost" oil from the vicinity of the device. Once back at the beginning of the tank, the oil was decanted from the device and the Retention Percentage was computed.

Test Results

The testing at Ohmsett consisted of 20 runs with 17 providing oil containment results. Those results are summarized in Table 3. Both of the devices contained oil at speeds 2 to 3 times that of conventional oil boom. In addition, it was very evident from visual observation that had the gap opening been larger on both systems, it would have improved their performance,

Table 3 Representative segment's test results.

Test #	Device Type	Oil Type	Tow Speed (kts)	Waves	Retention Percentage
1	Full longitudinal	Sundex	1	No	35.93
2	Full longitudinal	Sundex	1.5	No	102.85
3	Full longitudinal	Sundex	2	No	110.46
4	Full longitudinal	Sundex	1.5	Yes[1]	92.59
5	Full longitudinal	Hydrocal	1.5	No	84.88
6	Full longitudinal	Hydrocal	1.5	No	72.24
7	Full longitudinal	Hydrocal	2	No	72.81
8	Full longitudinal	Hydrocal	2.5	No	81.19
9	Full longitudinal	Hydrocal	1.5	Yes[1]	70.46
10 [2]	Full longitudinal	None	3	No	
11 [3]	Short Longitudinal	Hydrocal	1	No	
12	Short Longitudinal	Hydrocal	1	No	78.22
13	Short Longitudinal	Hydrocal	1.5	No	90.35
14	Short Longitudinal	Hydrocal	2	No	105.65
15	Short Longitudinal	Hydrocal	2.5	No	103.71
16	Short Longitudinal	Hydrocal	1.5	Yes[1]	101.76
17 [4]	Short Longitudinal	Hydrocal	2	Yes [1]	
18	Short Longitudinal	Sundex	1.5	No	55.05
19	Short Longitudinal	Sundex	2	No	83.67
20	Short Longitudinal	Sundex	2.5	No	87.30

[1] Wave length = 32 feet, Wave height = 0.5 feet, Wave Period = 2.61 seconds

[2] Test number 10 was a high speed hydrodynamics test during which oil was not used.

[3] Test number 11 was aborted due to problems with the oil distribution sytem.

[4] Test number 17 was a high speed wave test which was aborted when the device began to break. Repairs were made and testing continued but this test was never repeated.

especially in waves and at low speeds. In run 18, for example, below and above water observations showed that the gap jet was insufficient to clear accumulated heavy, viscous Sundex from the containment region just above the gap. This inhibited further oil flow in through the gap opening. High speeds and/or larger gap openings were seen to alleviate this problem.

It should be noted that there was some scatter in the Retention Percentage results (i.e. results over 100 percent). This was due to the relatively small volume of oil used in these tests in comparison to what Ohmsett normally would use (a necessity because of the relatively small size of the segments). Visual observations of the higher speed tests, however, were consistent with the Retention Percentages mentioned. Also, the low Retention Percentage for the first run was due in part to test methods still being worked out, particularly at the stops and during back up.

Test 10, the high speed hydrodynamics test, was intended to explore strength issues of these devices. The full longitudinal representative segment was chosen to be the sacrificial lamb and was run at three knots. The device's outside port longitudinal member broke in half during the middle of the run. This graphically illustrated the amount of force that these outside members were sustaining. Similar lessons were learned during test number 17, a high speed wave test with the short longitudinal system. During this test it's horizontal baffle began to separate from the outside longitudinal. This test was scrubbed to prevent further destruction of the device which still needed to make all of its Sundex runs. But the results were clear: the outside longitudinals, and their attachments are under great stress and need to be designed to handle such loads.

All of that said, it was felt the tests were very successful and that further development of flexible oil barriers was warranted. Though both systems performed well, particularly at the high end of the test speeds, a slight edge was given to the short longitudinal system in terms of overall ability to contain oil.

4. A FULL-WIDTH FLEXIBLE BARRIER

Design Rationale

The Ohmsett tests had shown that the short longitudinal segment was very effective at containing oil, and in view of its simplicity and smaller "hard" components, it was chosen as the basis for the full-width flexible barrier. The new challenge was to expand this design from just a segment, to a full-width barrier. This was not a trivial undertaking. Unlike a stiff system, a flexible barrier cannot sustain transverse shear forces. The solution is to make the principal tension members catenary curves in plan view. Thus, much like standard oil boom, the transverse drag forces are sustained by the tension force acting through the curvature (Cross and Holt, 1970; Goodwin, 1991; Swift et. al., 1992). So the full-width barrier prototype had to have its principal tension members (i.e. the chain in leading edge of the horizontal baffle, the submergence plane, and the rear buoyancy) catenary in shape.

Additionally, the Ohmsett tests had shown that the gap openings of both of the segment systems needed to be enlarged. Since there was not time to investigate what the ideal gap opening would be, it was decided to double the opening used in the segment systems.

Another design consideration was modularity. The prototype was to be modular, for ease of manufacture, transport, and assembly. Along these same lines, the prototype was to be composed of standard, available parts whenever possible to help ease manufacturing.

A final design consideration was the size of the Ohmsett tank. The plan was to return to Ohmsett to test the prototype, and so it needed to fit in the tank. This requirement defined the width of the device, and to some extent the length of it.

The Scale Model

Since this was the first attempt at building a device of this size, and needing to test the catenary concept, it was decided to build a 1/5th scale model of the prototype and test it in the UNH tow tank. It was hoped that the model would reveal any potential problems which might arise from expanding the representative cross section to full-width in the cross current direction. In addition, these tests would allow the design team to experiment with a few new ideas which had come up since the last tests, without risk to the prototype's final success.

The model's design was based upon the short longitudinal representative segment. Its tension members were made to form a catenary shape in the cross current direction, and as such, all its curves followed the catenary formula (see Figure 10). The new ideas which were to be tested involved the way the submergence plane was attached to the intermediate longitudinals, and the way the intermediate longitudinals were attached to the horizontal baffle. Up to this point these attachments had been rigid. But, based upon observations made during the Ohmsett tests it was surmised that this would not be necessary. Instead the submergence plane would be attached to the intermediate longitudinals at only two points, and the longitudinals would be attached to the horizontal baffle by passing the horizontal baffle's tension chain through a eyebolt on their underside. This would allow the longitudinal some freedom of movement, yet still support the

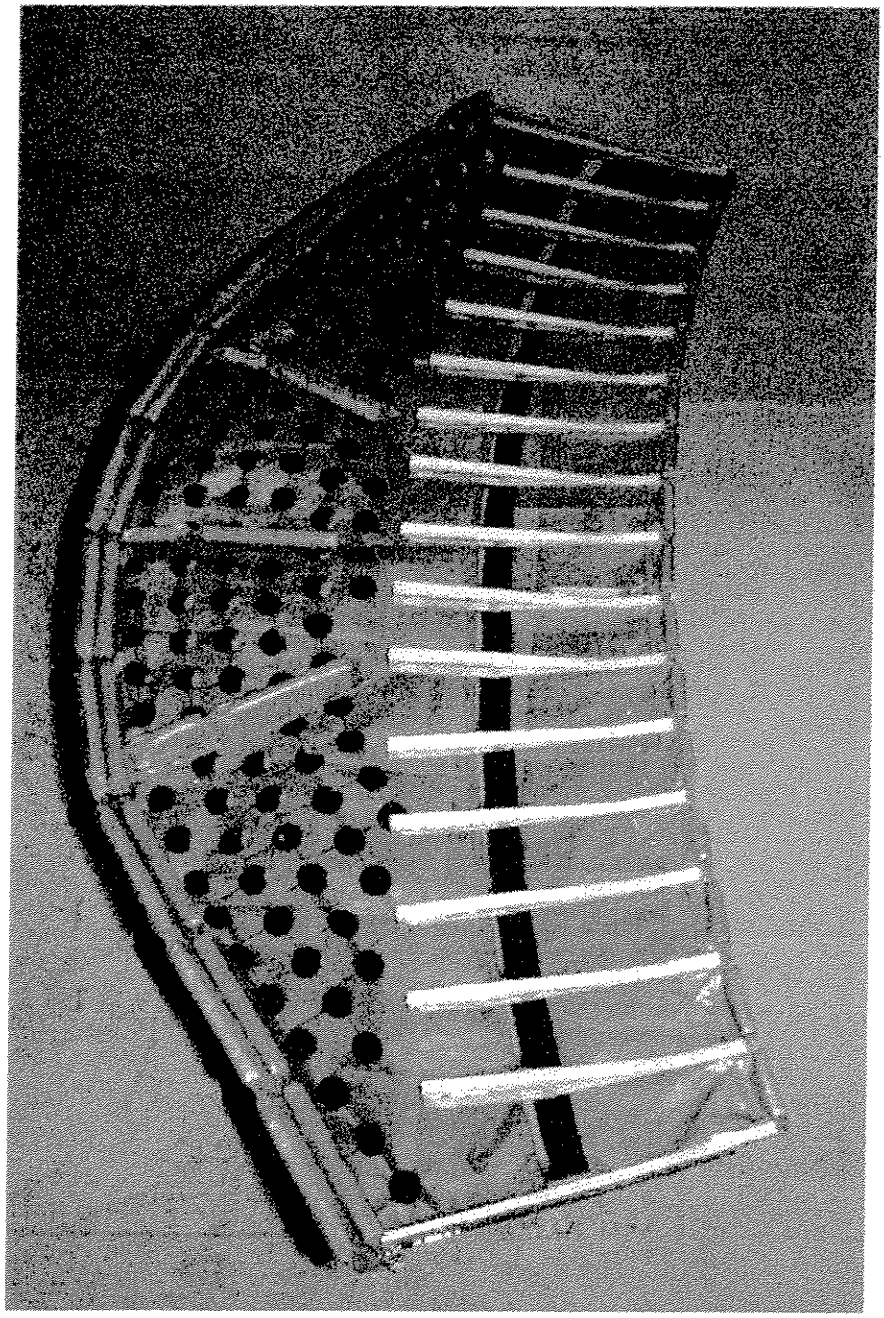


Figure 10 The scale model of the full-width prototype.

horizontal baffle. Both of these modifications, if successful, would help improve the modularity of the eventual prototype.

The model was built with wooden members, and skinned with an inexpensive plastic sealed fabric. The tension member at the leading edge of the horizontal baffle was wire. The aft barrier was made from 1/5 scale oil boom, which was constructed from the same fabric as the model, foam floatation, and a small chain for ballast. The attachment of the submergence plane to the longitudinals was done mechanically at the leading and trailing edges only, while the wire tension member ran through small eyes on the intermediate longitudinals as was discussed above. Finally, the rear booms were attached to the horizontal baffle with small gage zip-ties.

Hydrodynamic tests of the model were conducted in the UNH tow tank. The model was towed on the surface of the water where wave effects and inertial forces predominate, and there were no collection/retention experiments with this model which would have emphasized frictional forces, interfacial tension and density differences. Thus, Froude scaling was employed to ensure that the model and the eventual prototype were operating at corresponding speeds. The relationship between these speeds was;

$$V_{model} = V_{prototype} * (1/5)^{1/2}. \tag{1}$$

As a result, the model tow speeds and their corresponding full scale speeds were the following:

Model Speed (knots)	Full Scale Speed (knots)
0.204	0.456
0.408	0.912
0.612	1.368
0.816	1.825
1.02	2.280
1.23	2.750

Repeat tows were conducted at many of these speeds as lessons were learned and modifications were tried.

The results of these tests were very encouraging. The catenary shape performed well, was stable and sustained the drag forces with no problems. The intermediate longitudinals, and their new attachment systems, also worked quite well. In total, the model held its shape without difficulty.

Problems did arise at high speeds, though. At about 1.8 knots full scale speed, the rear barrier was overwhelmed and water flowed over it. To solve this problem, while still using standard available parts, it was decided add another boom to the rear of the device. This pushed the speed at which the barrier was overwhelmed up to about 2.5 knots full scale speed, well over the 2 knots at which we were hoping to test the prototype.

Another problem which developed at increasing speeds involved the horizontal baffle. It developed a wave motion which became severe at higher speeds. To solve this, small standard booms were attached longitudinally to the horizontal baffle to dampen out the wave action as seen in Figure 10. Battens were also tested to solve this problem with good success, but in the end the small boom sections were easier to use.

Full-Scale Design and Construction

With the success of the 1/5th scale model tests, the prototype became a scaled up version of the model, as can be seen in Figure 11 and 12. As the figures illustrate, the prototype's curves were catenary in shape, as was the model's. It had a double boom rear floatation system, and utilized small longitudinal booms to dampen out any wave action in the horizontal baffle, as the model had done. The intermediate longitudinals (Figure 13) were scaled up versions of the ones used in the model and utilized the same attachment systems which had proven so successful during the model tests. In addition, the criteria for the spacing of the intermediate longitudinals came from the model. In almost every way the prototype was a bigger version of the model. The biggest difference between the two was the design of the outside longitudinals (Figure 14). The Ohmsett tests had proven the importance of the strength of these outside members, so the prototype's were strengthened beyond what had been used in the scale model.

Another feature of the prototype which differed from earlier designs was having the reserve buoyancy at the top of the submergence plane be easily removable instead of permanently attached. This meant that at the conclusion of testing, the devices would be much easier to clean. The foam could be removed and disposed of (or cleaned separately), and the foam pockets could be properly power washed. In addition, this feature allowed not only flotation removal, but also

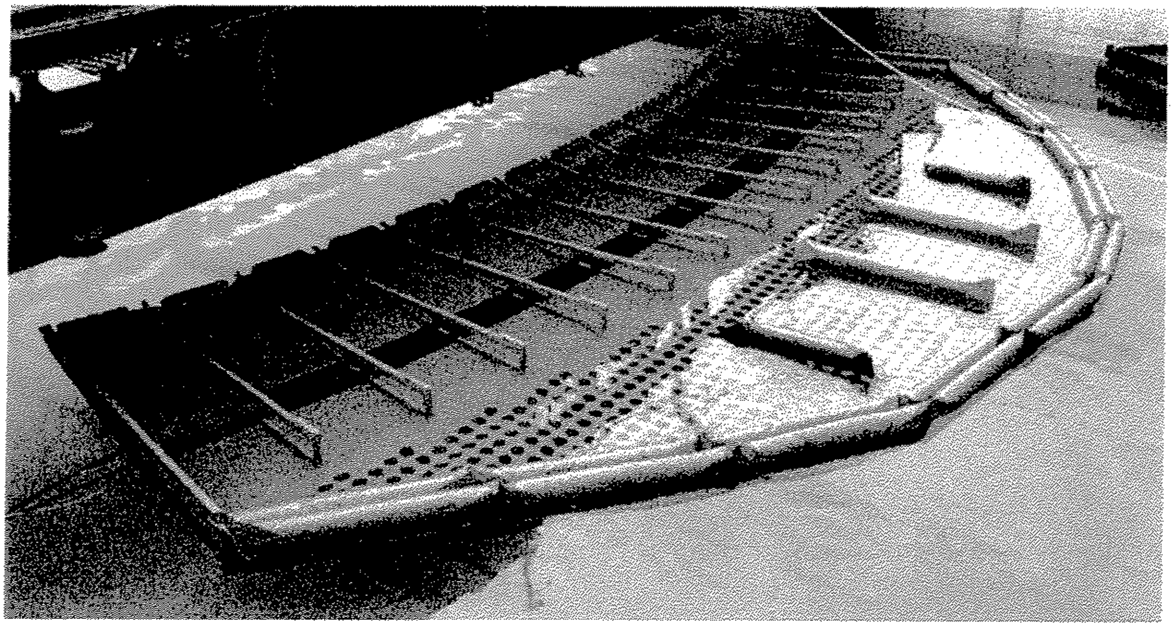
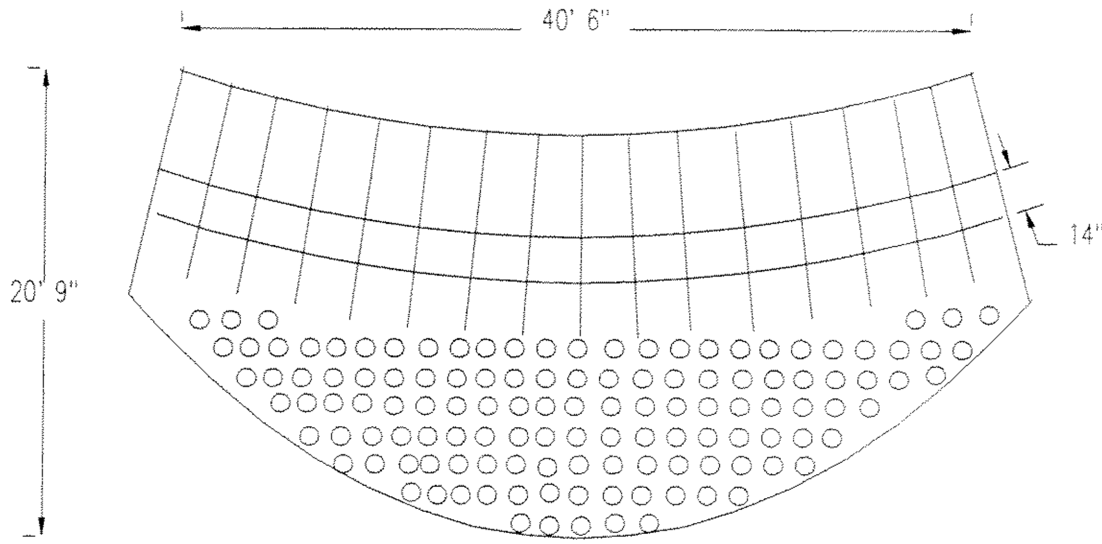
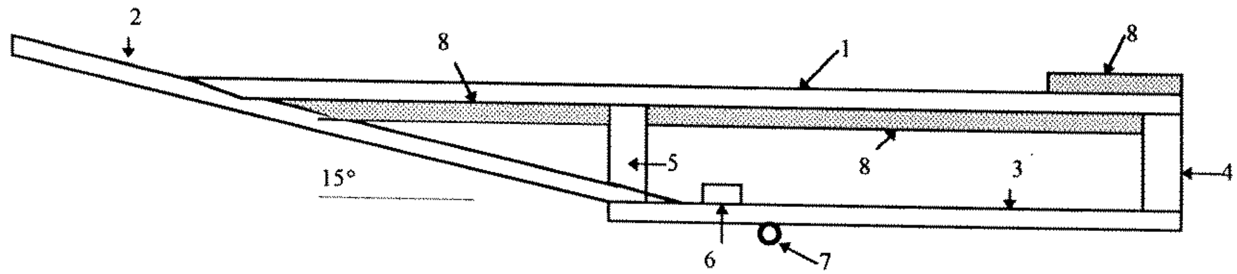


Figure 11 The full-width prototype.



Diameter of holes = 4"

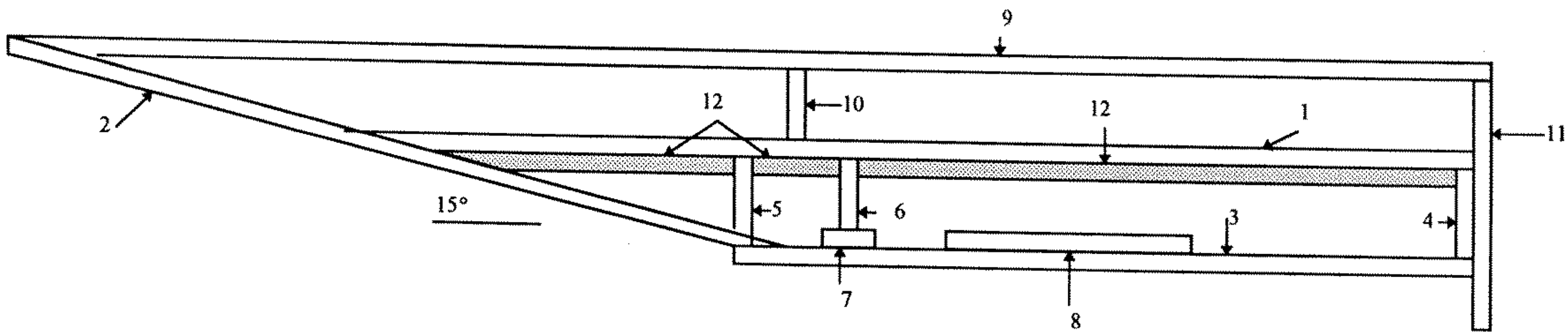
Figure 12 Major dimensions of the full-width prototype.



Key:

1. 0.75" x 1.5" x 7', 15° bevel
2. 0.75" x 1.5" x 5' 6.75", 15° bevel
3. 0.75" x 1.5" x 3' 4.25"
4. 1.5" x 1.5" x 11.75"
5. 1.5" x 1.5" x 11.375", 15° bevel
6. 5 lbs. lead ballast
7. eye bolt
8. 1.5" x 2" foam

Figure 13 The intermediate longitudinal (not to scale).



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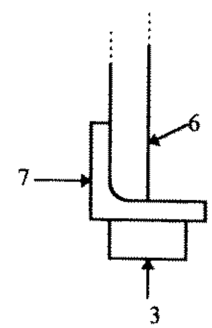

1. 1.5" x 3.5" x 8' 7.25", 15° bevel
2. 1.5" x 3.5" x 5' 7.625", 15° bevel
3. 1.5" x 3.5" x 5' 0.5"
4. 1.5" x 3.5" x 11.5"
5. 1.5" x 3.5" x 10.375", 15° bevel
6. 1.5" x 3.5" x 11.25"
7. 0.25" x 4" x 4" steel angle
8. 30 lbs. lead ballast
9. 0.75" x 1.5" x 10' 1.625"
10. 1.5" x 1.5" x 3.75"
11. 1.5" x 1.5" x 2' 1.25"
12. 3.5" x 4" foam

Figure 14 The outside longitudinal (not to scale).

removal of the whole submergence plane from the longitudinals. Thus it could be folded into a small package for shipping.

As was the design goal, the prototype was built with standard available parts. The longitudinals were built from wood and were made independently stable with closed foam flotation and lead ballast. The material used to skin the device was standard oil boom fabric provided by JPS/OILTROL Inc. It was provided to UNH in one big piece which only had to be cut to shape and attached. The one seam that had to be manufactured here was the seam used to enclose the tension chain at the leading edge of the horizontal baffle. There was initially some discussion as to the best way to do this. JPS/OILTROL Inc. was espousing the benefits of staples. There was great skepticism as to the strength of this option, so tests were devised and conducted to establish whether this was a viable alternative. A description of these tests can be found in Appendix 1. The results showed that stapling was in fact strong enough to be used for this seam.

As was proposed, the prototype was designed with modularity in mind. The whole thing could be broken down and shipped as its individual parts (i.e. the submergence plane, the horizontal baffle, the intermediate longitudinals, the end longitudinals, the rear double boom, the small longitudinal booms, and finally the submergence plane reserve flotation) and then reassembled at the test site, which in this case was Ohmsett.

5. FULL-SCALE PROTOTYPE TESTING AT OHMSETT

Measurement Methods and Test Protocol

The culmination of the third year effort to develop a full-width, flexible barrier was the evaluation test program done at Ohmsett. Would a full-width, flexible oil barrier, based on the submergence plane concept, collect oil at speeds two to three times greater than the critical speed of standard oil boom? The model tests indicated that the prototype should have no problems holding its shape. And the segment tests, during the previous trip to Ohmsett, indicated that it should collect oil. But none of that work had been done with a device this large. It was hoped that the results of those earlier tests would translate, but that remained to be seen.

The prototype was shipped to Ohmsett (along with all the tools and parts necessary to fix or change any part of it) in a 14 foot box truck. Upon arrival a small team of workers fully assembled it, in driving rain, in one and a half hours. This alone satisfied project goals which dealt with ease of transportation and assembly. Once assembled, it was attached to the main bridge in the same way as the two representative segments had been (Figure 15), and then it was ready for testing.

The tests were to follow the same protocol as the tests done on the representative segments during the last trip to Ohmsett. The only exception was that during this series of tests the oil would be removed from the device at the far end of the tank. This eliminated the need for special tow back procedures.

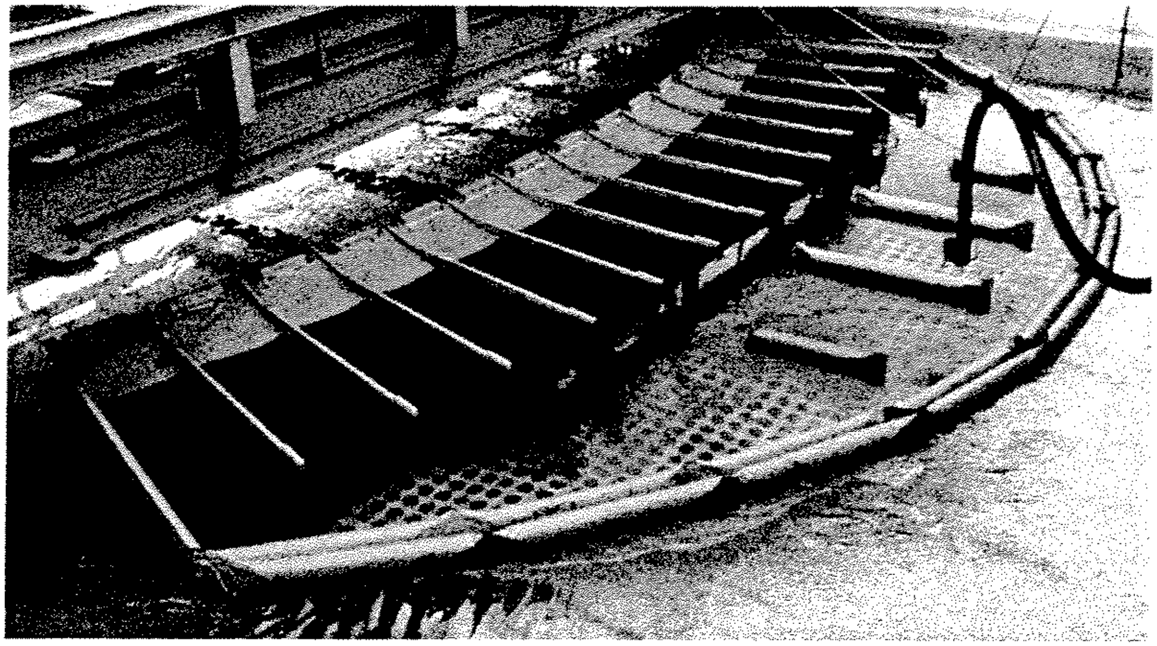

Figure 15 The full-wdth prototype with Hydrocal.

Testing would begin at one knot (the speed at which even the best of standard oil boom would fail), and would continue through the maximum anticipated speed of the device (based upon the model tests, two to two and a half knots). The oils used would once again be Hydrocal and Sundex (see Table 2), and the same waves profiles would also be used. Finally, the quantifier would once again be Retention Percentage (see Section 3).

Test Results

Ten runs were made, as can be seen in Table 4, of which eight were relevant to the above mentioned test protocol. Generally, the results were quite good. However, all who watched with the tests were surprised at the numerical results of the Hydrocal runs. The Retention Percentage numbers for these experiments were not high. But, visual observation, and the video record, seemed to indicate very little, if any, losses during these tests. Further confusing the issue was the fact that of the two oil types, Hydrocal has historically been the easiest to capture, so if these numbers were correct one would expect to see comparatively low Retention Percentages for the Sundex tests, as well. This was not the case. In fact, the Sundex test results were quite good.

Upon inquiry, it was discovered that an inexperienced person had decanted the water from the holding tanks and collected the stratified-weighted samples for these Hydrocal tests. These samples require skill to obtain accurately and are used to determine the percentage of water and "other material" mixed in with the captured oil. It is this percentage that is used to calculate the net volume of oil recovered from the gross volume of oil recovered, and it is the net value that is divided by the volume of oil introduced to obtain the Retention Percentage. So an error in

Table 4 Full-width catenary barrier's test results.

Test Number	Oil Type	Tow Speed (kts)	Waves	Retention Percentage
1	Hydrocal	1	No	64.31
2	Hydrocal	1.5	No	78.34
3	Hydrocal	2	No	77.05
4	Hydrocal	1.5	Yes[1]	40.16
5	Sundex	1	No	69.95
6	Sundex	1.5	No	97.72
7	Sundex	2	No	98.94
8[2]	Sundex	2.5	No	
9[3]	None	2.5	No	
10	Sundex	1.5	Yes[1]	88.14

[1] Wave Length = 32 feet, Wave Height = 0.5 feet, Wave Period = 2.61 seconds

[2]Test number 8 was a high speed test which was aborted.

[3]Test number 9 was a high speed hydrodynamic test.

sampling has a direct effect on the Retention Percentages. Sampling error could explain the apparent contradiction between visual observations and measured results. An indication of this, and the extent of the error, can be estimated from the following. During the third run enough oil was contained by the device that it needed to be off-loaded into two holding tanks on the auxiliary bridge instead of just one. One of these tanks was sampled using the stratified-weighted method. The other was sampled by a straight-forward, representative grab sample technique. The difference was drastic. The grab sample indicated that the percentage of water and "other material" in the oil was 9%, while the sample requiring skill but done by the inexperienced person indicated that the percentage of water and "other material" was 37%. Had both tanks been grab sampled with the same 9% result, the Retention Percentage for test number three would have been 96.29% instead of 77.05%.

Aside from this issue, these tests were a great success. There was excellent visually observed retention at speeds up to two knots with the wake having virtually none or negligible amounts of oil. The numerical Retention Percentage results for Sundex at one and a half and two knots are the highest that can be practically achieved. The device was only limited beyond two knots by the freeboard and buoyancy of the aft barrier which can easily be improved. At 2.4 knots exit flow washed out over the rear barrier - a condition preventable by increasing rear barrier freeboard and reserve buoyancy. Interestingly enough 2.4 knots was the approximate speed at which the 1/5 scale model tests predicted this would occur. The device contoured the waves quite well and, as with the higher speed tests, the results of the wave tests were only limited by the freeboard and buoyancy of the aft barrier. There were no major strength problems observed during these tests, and the excellent results would indicate that the gap opening was adequate. In general, these tests were very encouraging.

6. STANDARD OIL BOOM FAILURE EXPERIMENTS

Purpose and Approach

The purpose of this part of the research program was to generate data detailing how standard oil booms ultimately fail to hold oil slicks as current speed is increased. The data is to be used by URI collaborators for comparison with their numerical models for the interaction of oil slicks with standard booms. Though there have been many experimental studies of these processes done in the past, none provide the detailed documentation needed for a rigorous comparison with the more recent Grilli et al. (1996, 1997) two-dimensional computer simulations. High resolution slick thickness as a function of position and time for a complete set of recorded fluid properties, environmental parameters and boundary conditions are needed.

The focus of this collaborative work was on high viscosity oils since disasters often involve unrefined product or oils that have been subject to weathering. Experiments by Delvigne (1989), using a wide variety of commercially important oils, show that oil booms fail to contain high viscosity oils by a process of "failure by critical accumulation". This failure mode, therefore, was of principal interest.

The approach was to conduct experiments in the UNH recirculating flume which has clear plastic sides at the test section for observing slick profiles. The intent was to achieve two-dimensional slick geometry with no variation across the flume. The UNH recirculating flume, shown schematically in Figure 16, is 12.2 m (40 feet) long, 1.22 m (4 feet) wide and 1.22 m

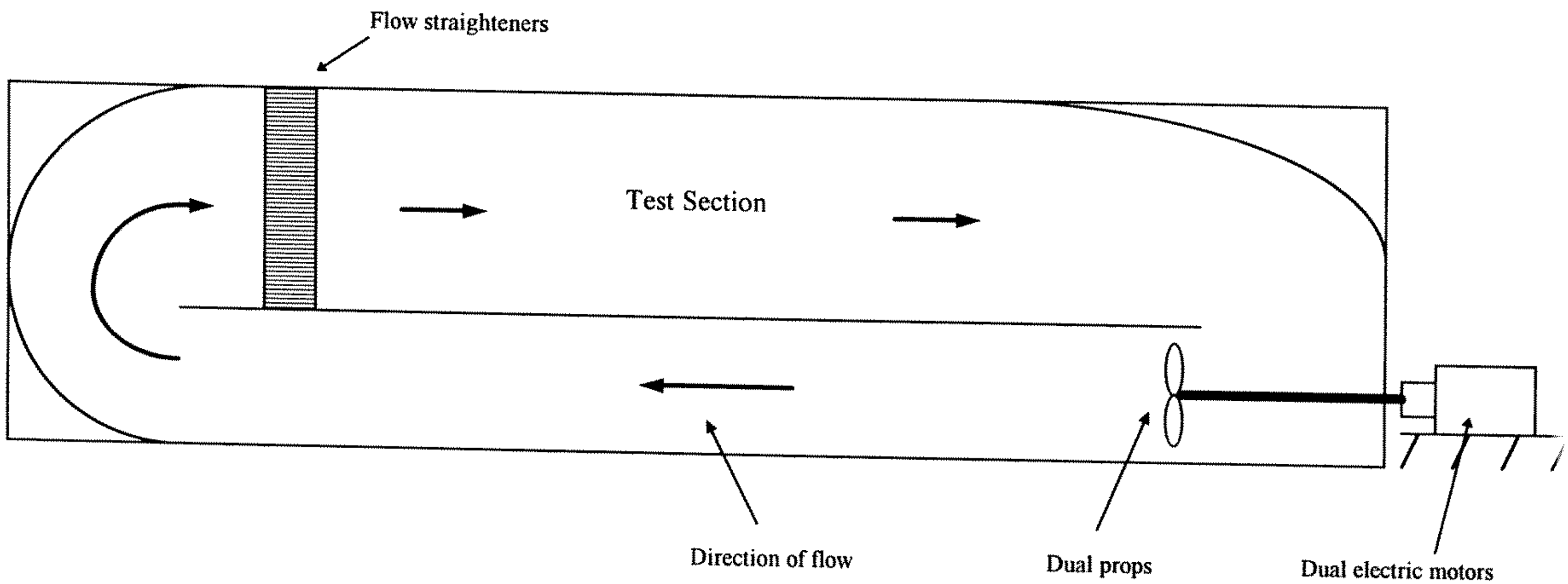

Figure 16 Schematic of the UNH recirculating flume.

(4 feet) in overall height. The flow is driven by two counter-rotating propellors powered by two variable speed electric motors. The system was calibrated so that flow speed was known as a function of motor frequency which was precisely controlled electronically. This facility is dedicated to oil spill research, and petroleum products are used routinely.

The experimental program was initiated with a sequence of preliminary tests to develop the oil experiment protocols. The standard oil boom/skirt configuration was represented by a plane, constant draft panel positioned vertically across the tank. Using small plastic beads to simulate oil droplets, questions regarding secondary flows, two-dimensionality and slick size were addressed. Preliminary tests were conducted on December 20, 1996, February 28, 1997 and, following barrier alterations and tank calibration, on March 14, 1997.

Experiments using real, high viscosity oils were carried out on May 2, 1997, July 24, 1997 and July 31, 1997. Profile shape was recorded using a computerized optical system consisting of a high-resolution video camera, a frame grabber and a personal computer with expanded memory. Experiments were also logged using two standard video cameras placed to view the slick from perpendicular directions. Still pictures were taken of major activities, observations and events using a 35 mm camera.

Recorded profile images were then examined, and those suitable for comparison with the URI two-dimensional models were identified. Software was written to analyze the images and to compute thickness as a function of position. Image sequences, UNH-developed programs and methods for using both UNH and commercial image processing software were communicated to the URI team.

Preliminary Experiments with Beads

Test methods were worked out using 3.2 mm, black plastic beads having a specific gravity of 0.93. Beads had been used in previous flume work (see, for example, Swift et al., 1996) where their usefulness in preliminary studies was demonstrated. The vertical, plane barrier consisted of a 1.91 cm thick panel placed across the flume (perpendicular to the sides) at uniform draft. We were guided in part by the flume results of Delvigne (1989) which showed "failure by critical accumulation" at speeds less than 31 cm/s using barrier drafts in the range of 7 to 13 cm.

In the first preliminary experiment carried out on December 20, 1996, approximately 1 liter of beads were introduced in front of a 15 cm deep barrier. Current speed at 7 cm/s amounted to a slight drift forcing a "slick" to collect up-current of the barrier. The head of the slick (up-current edge) took on the top-view shape of the letter "M" (looking down with the current moving from the bottom to the top of the "M"). At 13 cm/s, there were random swirls but no organized entrainment of beads. At 30 cm/s, the slick compressed and intermittent corner vortices formed at the intersection of the sides with the barrier. The sidewall/barrier vortices entrained beads under the barrier. At 40 cm/s, corner vortex entrainment was continuous but with varying strength.

The corner vortices were caused by accumulation of sidewall boundary layer vorticity in the corner stagnation area. This is an artificial result of the flume-barrier configuration and is a serious problem in achieving the desired two-dimensionality.

On February 28, 1997, a second preliminary experiment was conducted in which the slick size was increased to determine whether greater slick volume would overcome the undesirable three-dimensional secondary flows. This was suggested by previous oil barrier research showing that the slick length (in the direction of current) must be at least 5 times the draft to avoid the effects of a stagnation region just up-current from the barrier.

Approximately 3 liters of beads were introduced in front of the barrier with draft reduced to 7.6 cm. At 13 cm/s, the bead "slick" was 58 cm long (over 7 times the draft); the leading edge in top-view was much closer to a straight line across (perpendicular to the flume sides), and there were no corner vortices. At 30 cm/s, however, the slick compressed; the "M"-shape leading edge returned, and vortex entrainment occured at the corners. Greater slick size, relative to barrier draft, definitely resulted in a more two-dimensional shape, but there were still problems, particularly with corner vortex entrainment.

The corner vortex entrainment problem was addressed by placing rubberized horsehair in front of the barrier as suggested by Milgram and Van Houghton (1978). A uniform layer of horsehair extended the full width of the flume and at the full draft of the barrier.

On March 14, 1997, the horsehair concept was tested using a horsehair/barrier draft of 6.4 cm. Approximately 2 liters of beads were introduced and produced a straight leading edge slick at 7 cm/s. At 22 cm/s, the slick compressed lengthwise (in the direction of current) but maintained the same two-dimensional longitudinal-section across the width of the flume. At 30 cm/s, entrainment loss at the leading edge commenced, but there was no corner vortex entrainment as long as the horsehair did not become saturated.

Since this configuration produced a two-dimensional slick without sidewall/barrier corner vortex losses in the speed range of interest, it was judged suitable for "real oil" experiments. In these tests, the horsehair layer itself would be regarded as the leading side of the barrier.

Oil Experiment Methodology

Oil experiments were completed in the UNH recirculating flume using the set-up shown in the Figure 17 photo. The plane barrier across the flume is 6.4 cm deep. The horsehair also has a 6.4 cm draft and is 20 cm long in the direction of the current. The horsehair is hung from horizontal rods inserted at the waterline into the vertical panel. Experiment activities were logged by a standard video camera placed on planks across the flume to the left (up-current) of the slick and looking down on the slick and barrier. A second standard video camera was placed on the near side beneath where the Figure 17 photo was taken. These cameras were mounted on tripods and were run continuously during the experiments. Black and white still photographs were taken of significant events and processes using a 35 mm camera. The slick profile against the near side clear plastic tank wall was recorded by a high resolution video camera with output directly to a

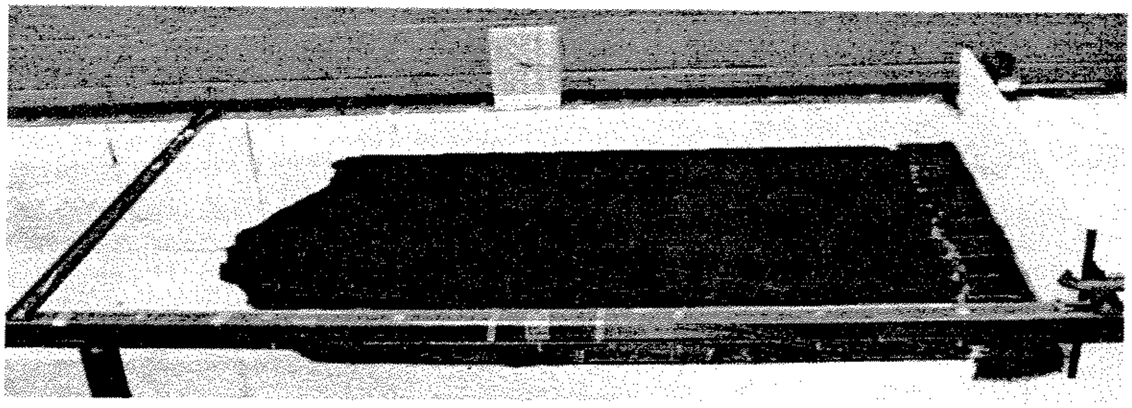

Figure 17 Flume experiment set-up and initial slick shape.

computer. Experiment 1 took place on May 2, 1997 using Sundex oil; Experiment 2 on July 24, 1997 using Silicone 10,000 lubricating oil, and Experiment 3 on July 31, 1997 using Sundex. Parameters for the three experiments are summarized on Table 5.

Both oils have properties such that loss of oil would be due to "failure by critical accumulation". Sundex has a specific gravity of 0.96 and had a kinematic viscosity of 20,000 centistokes during Experiment 1 and 15,000 centistokes during Experiment 2 (when it was warmer). Silicone 10,000 has a specific gravity of 0.97 and a kinematic viscosity of 10,000 centistokes. A volume of 37.1 liters of Sundex was used in Experiment 1, and 30.3 was used in Experiment 3. This gave an initial (drift speed) slick length of approximately 2 m with a thickness on the order of 1 cm. In Experiment 2, the Silicone 10,000 volume was reduced to 14.4 liters in order to shorten the slick length so that it would be earier to get the entire slick length into the high-resolution camera field of view.

Prior to the oil experiments, the flume was recalibrated with the barrier in place. Incident flow was measured by a laser doppler velocimeter and (as a check) by timing neutrally bouyant particles. Calibration was achieved by relating measured steady state flow velocity to the frequency set on the AC electric motor speed control. A common time was established by placing a clock within view of the side cameras. The top view video camera's internal clock was synchronized to this external clock. Water/oil temperature was recorded for each experiment. In Experiment 3, markers were placed every 20 cm along the flume rail for reference, and the

Table 5 Parameters for oil experiments in the UNH flume.

Parameter	Experiment 1	Experiment 2	Experiment 3
Channel width (m)	1.18	1.18	1.18
Water depth (cm)	76.2	75.0	76.2
Barrier draft (cm)	6.4	6.4	6.4
Oil volume (liters)	37.1	14.4	30.3
Temperature (deg C)	20	22	22
Water density (g/cm^3)	1	1	1
Oil density (g/cm^3)	0.96	0.97	0.96
Oil kinematic viscosity (centistokes)	20,000	10,000	15,000
Oil-water surface tension (dynes/cm)	34	34	34

position of the horsehair/barrier was clearly distinguished from the black oil by placing a contrasting white sheet of paper over the horsehair end area.

The optical measurement system consisted of a high resolution, back and white, Pulnix video camera, a frame grabber to transfer the images, a personal computer with expanded random access memory (RAM) to receive the images and image processing software. Complete specification of the optical system components has been documented by Michelin and Stott (1997). In operation, each frame was transferred directly to the computer's RAM. During breaks in the data acquisition, the images were saved to the computer's hard drive. Each frame image could then be processed later to yield slick thickness as a function of horizontal position.

In Experiment 1, the camera was placed to face the clear plastic side of the tank test section. The distance back from the tank was determined as the minimum necessary to include the entire 2 m long initial slick with the zoom lens at the widest setting. The camera was not moved nor the lens reset during the experiment. In Experiment 2, angle problems at the two extreme ends of the slick were reduced by using a shorter slick and by moving the camera back. Because of an obstruction, a very large mirror was needed to redirect the rays along a path having the desired distance. In Experiment 3, the camera was again placed perpendicular to a slick approximately the same size as in Experiment 1. In Experiment 3, however, resolution was increased to 11 pixels/cm by moving the camera closer and using a longer focal length. The drawback here was that the entire full-length slick could no longer be viewed at once, and the camera tripod had to be moved during the experiment. At low speeds (longest slick lengths), this required viewing the slick in three parts - head, middle and near-barrier. In all experiments, distance calibration information was obtained by recording a solid black 5 cm diameter circle placed on the tank wall near the slick profile.

The experiments started by deploying the oil while flow speed was 7 cm/s - a gentle drift with just enough movement to form the slick as it came against the barrier. Flow speed was then increased in 1.625 cm/s steps. With each change in speed, optical data was acquired to record the transient slick adjustment dynamics. Another sampling burst was taken when the slick had fully achieved the new equilibrium profile. At near critical velocity speeds, the dynamics were continuous, and optical data acquisition was only stopped to save files from RAM to hard drive and, in Experiment 3, to reposition the camera. When the oil moved beneath the horsehair/panel, the barrier was considered to have failed, and the experiment was terminated.

Observations

In Experiment 1, Sundex oil was introduced to form the slick while the flume ran at 7 cm/s (just fast enough for the oil to collect in front of the barrier). The speed was then increased in increments of 1.625 cm/s to a maximum speed of 20 cm/s (which was observed to be the critical velocity). After each speed increase, observations were made as the slick deformed. Because of the viscosity (20,000 centistokes), this process was very slow with time scales on the order of minutes.

The fully formed slick at 7 cm/s is shown in Figure 17. It was approximately 2 m long and 1 cm thick. Some secondary flows persisted preventing a completely ideal two-dimensional situation. The shallow "M" shape of the leading edge top-view was a common feature of these flume experiments. This shape had been observed in the preliminary tests with beads where it had become extreme with decreasing slick volume. In Experiment 1, the large volume of oil used minimized cross-channel variations.

As the current speed was increased above 12 cm/s, the slick was compressed and the characteristic "head wave formed as seen in the Figure 18 photo. Early in the experiment, there were also occasional downward protrusions which can also be seen. These never grew to the point of breaking off, and eventually the slick underside stabilized.

In general for speeds below 16 cm/s, the speed step increase would introduce slick compression and a change in profile shape (including headwave growth). The profile would then eventually come to equilibrium. Above 16 cm/s, dynamics, though very slow, were continuous. Waves would form, evolve and move oil volume towards the barrier.

At the highest speed, 20 cm/s, well-defined, scalloped waves formed as shown in Figure 19. When these moved under the horsehair portion of the barrier, the barrier was considered to have failed and the experiment was concluded. In general, Experiment 1 slick length, profile shapes and velocity at failure were well within the range of "critical accumulation" results presented by Delvigne (1989).

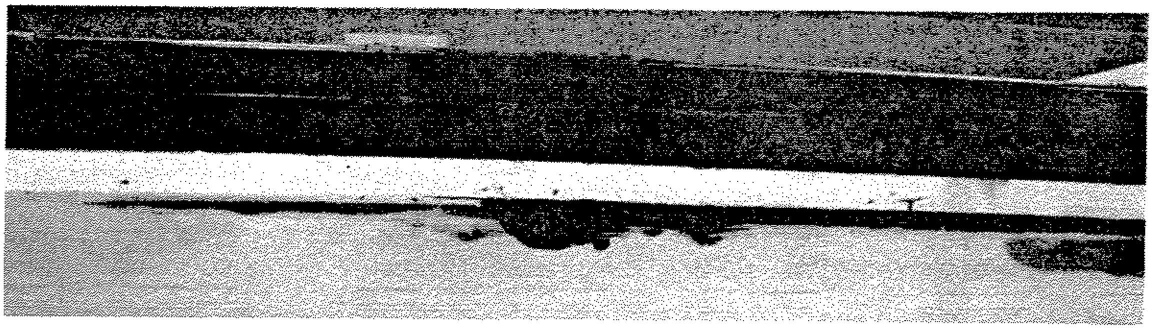

Figure 18 Headwave formation at slick leading edge.

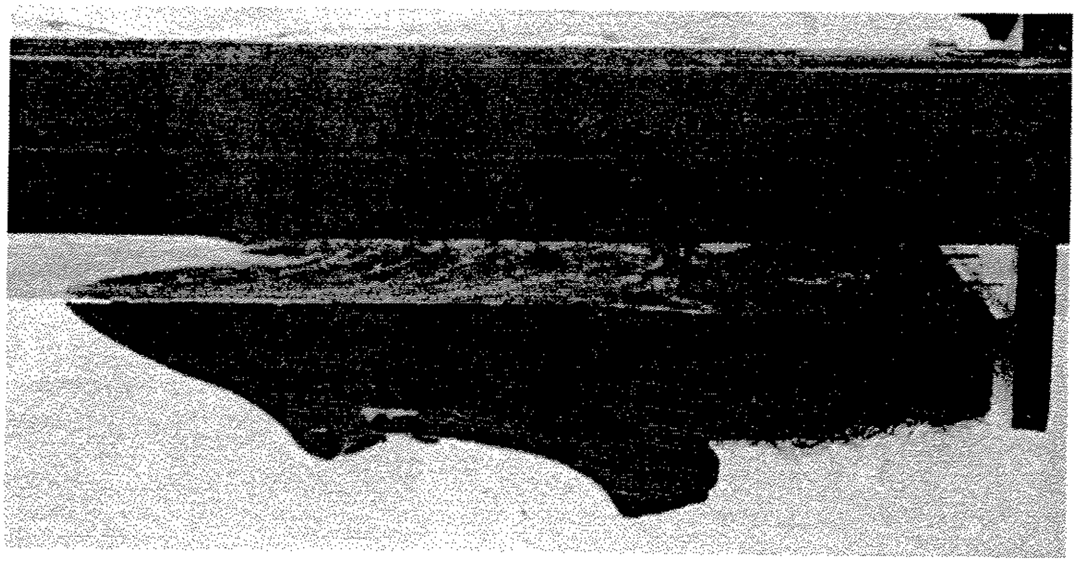

Figure 19 Scalloped wave growth at failure velocity.

In Experiment 2, a silicone oil was used having half the kinematic viscosity (10,000 centistokes) of the Sundex in Experiment 1. A smaller amount of oil was employed with the idea that the slick would be shorter so that the profile recording camera could zoom closer and get more resolution without overfilling the frame. The stagnation region just in front of the center of the barrier, however, was able to exert a strong influence. As in prior experiments, its effect became more pronounced with a shorter slick. In this experiment, the three-dimensional distortion caused significant leading edge and profile variations across the width of the flume. In fact, there was not sufficient uniformity across the flume for a rigorous comparison with the URI two-dimensional models.

Experiment 2 did, on the other hand, reveal some important qualitative results. The same basic processes and longitudinal section shapes were observed in this test as in Experiment 1 using the higher viscosity Sundex. The Sundex profiles appear, therefore, to be characteristic of the "critical accumulation" failure mode. The silicone oil merely reacted more quickly.

In Experiment 3, Sundex was used again since its behavior exhibited all the features of the "critical accumulation" mode of standard barrier failure. Because the temperature was warmer, the Sundex kinematic viscosity (at 15,000 centistokes) was actually intermediate between that of Experiment 1 and Experiment 2. The volume of oil was increased to nearly that of Experiment 1 to regain slick size and, therefore, the desired two-dimensionality.

In general, shapes and processes observed were similar to Experiment 1 except that initial slick length (at 7 cm/s) was somewhat shorter and continuous dynamics began at a slightly lower speed. This behavior was consistent with the lower viscosity.

The major differences were in changes made to improve the images taken. To get better resolution, the camera was moved closer and repositioned to cover each part of the slick. The camera zoomed in on the head region first, then was moved to cover the middle of the slick and then moved again to observe the portion up against the barrier. By coming closer, vertical resolution improved to 11 pixels/cm. This worked well when the slick was in stable equilibrium at low speeds (below 12 cm/s). It also was successful at the highest speed, just before barrier failure, since the camera could be close and still view the entire compressed slick without repositioning. At intermediate speeds, however, some slick dynamics could not be recorded.

The results useful for model comparison included complete (in parts) image data sets during equilibrium conditions and a single continuous record of the ultimate "failure by critical accumulation" dynamics. In addition, a concerted effort was made to eliminate stray marks and lines so that slick profile processing would be straighforward. For example, a contrasting white sheet was placed over the end of the horsehair/barrier to clearly differentiate its end area from the encroaching black slick profile.

Image Data Processing

The optical measurement system acquires a sequence of images with each image stored as a separate file. The time assigned to each image is the start time of the sequence (logged separately) plus the image file count number multiplied by the sampling interval. Each image file consists essentially of a 484 pixel by 768 pixel array with each position assigned a gray scale number from 0 to 256. Image data may be analyzed using MATLAB written programs. The images may also be displayed, printed and edited using commercial digital image software such as Paintbrush.

Selected images from Experiment 1 data were edited to remove stray black marks, reflections, shadows and background forms. The purpose was to "clean up" the images leaving only the oil slick profiles. This was completed for the slick profiles shown in Figure 20 which comprehensively illustrate all observed processes and characteristic shapes. Initial slick, compression, head wave formation, scalloped wave growth and oil movement to and eventually under the barrier are all shown. For speeds up to 16.75 cm/s the first profile represents shape right after the step up in speed, while the second profile is the equilibrium shape. Calibration information is also included by means of the 10 cm line and the 5 cm diameter circle. Ten images for the conditions of the first, third and fifth profile shown were also prepared so that statistical analysis could be performed. The Experiment 1 edited profile images were transmitted to URI over the Internet along with test parameters.

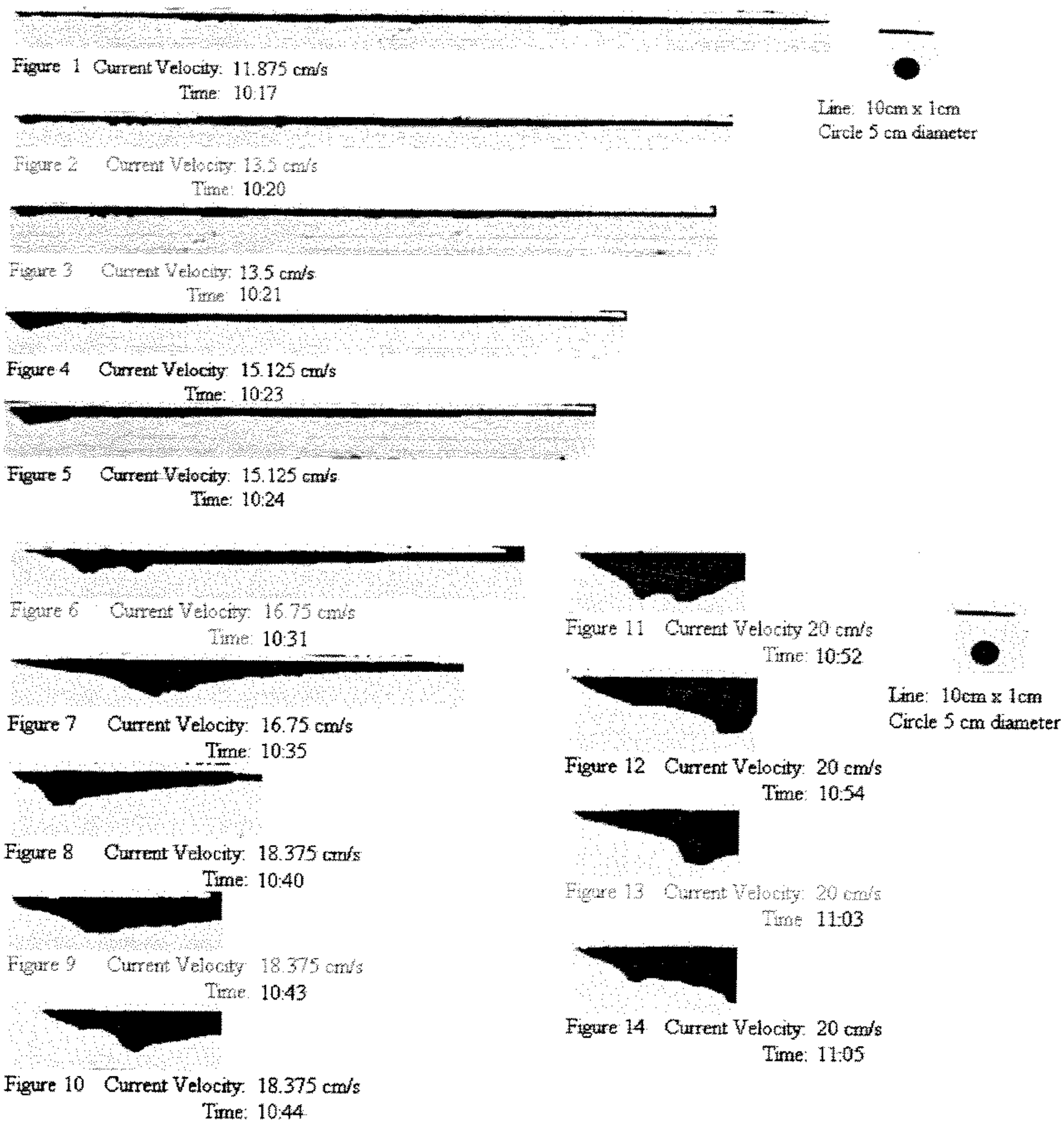

Figure 20 Experiment 1 representative slick profile images.

No data from Experiment 2 was suitable for comparison with the URI two-dimensional models. Three-dimensional variations, specifically profile variations in the cross-current direction, were too significant.

In Experiment 3, the effort to minimize extraneous dark areas during the experiment allowed original image data to be useful without editing. "Raw" footage during slick equilibrium conditions (11.4 cm/s) and near-failure dynamic conditions (15.7 cm/s) was saved on a CD and mailed to the URI collaborators. Thus statistical information during equilibrium conditions and actual time series for "failure by critical accumulation" were provided.

Each digital image of slick profile shape (at the time the image was taken) can be processed to yield thickness as a function of horizontal position. Analysis begins with calibration to convert differences in pixel position to distance. The 5 cm circle shown in Figure 20 was always included for this purpose. Note that digital displays do not necessarily have the same ratio of vertical height (in pixels) to horizontal distance (in pixels) as the Pulnix camera, so the circle can appear distorted. The next step is to define the gray scale criteria for what is dark enough to be considered part of the slick and what is (light) background. Analysis can then proceed column by column identifying the transition from background to slick and from slick to background. In Appendix II a MATLAB program is included which performs these functions. A second program is also included that implements a MATLAB routine for smoothing the slick profile. This software was discussed and shared with URI collaborators at the site visit meeting at UNH on October 21, 1997.

7. CONCLUSION

The second set of tests at Ohmsett showed that a full-width, flexible, oil barrier, based upon the submergence plane concept, could replace standard oil boom in areas where currents were present. The new design is capable of retaining oil at speeds 2 to 3 times the failure velocity of standard oil booms. In the development process, it was shown that these devices did not have to be difficult to handle: that, with modularity, they could be easily stored, transported, and assembled. It was also shown that their drafts, and thus size, did not have to be limited. This paves the way for much larger versions of these barriers, possibly even off-shore models.

In addition, some of the devices which were utilized to arrive at the final design, i.e. the flexible segments, also showed promise as stand alone systems. They could very easily be developed into small, inexpensive, skimmers.

All of these encouraging results lead to the conclusion that further development should proceed to elevate the design from a test prototype to a validated commercial product suitable for mass production. This will entail investigating better materials for construction, discovering the best way to deploy these devices in the field, and continuing to improve upon their logistical aspects. The next generation design should also incorporate improvements for performance such as, for example, increasing aft barrier reserve freeboard and buoyancy. Final evaluation should again be conducted at Ohmsett. Lastly, the parallel applications, such as small inexpensive skimmers, of this design should also be investigated, thus wringing the most benefit from this body of work.

The observations of standard oil boom "failure by critical accumulation" yielded digital images useful for comparison with URI two-dimensional numerical models. Results were consistent with previous laboratory work by Delvigne (1989), but provided much more detail regarding experimental conditions as well as actual slick profile shape. The next set of issues to be addressed are those of barrier draft and wave activity since these are of critical practical significance.

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APPENDIX I: SEAM TEST

Test Objective:

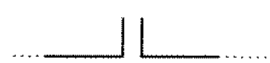
The objective of these tests were to establish if stapling was an effective method of binding two pieces of conventional oil boom material together.

Test Methodology:

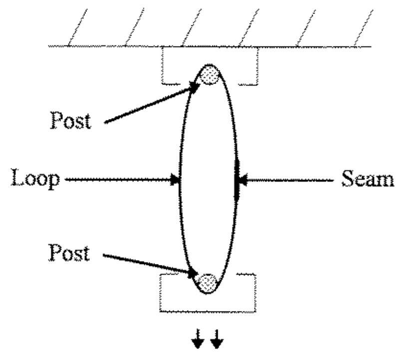
The methodology consisted of strength tests conducted with three different types of binding techniques;

a. traditional sewing
b. stapling, utilizing heavy duty 0.5 inch staples
c. stapling, utilizing standard staples.

Two types of seams were used for these tests;

a. Butt seams (seams in tension) 
b. Overlap seams (seams in shear)

The seams were created by connecting the two ends of 6" wide by 24" long strips so that they formed a loop. They were then tested on an Instron machine (model 1350) by putting this loop over two posts which were connected to the machine (see below).



The machine then pulled the bottom post away from the top one at a rate of .02 inches per second until the seam or fabric failed.

Though test objectives were addressed here without applying ASTM standards, there are applicable standards which may be used. Test protocols are described by ASTM Standard F715-95 “Standard Test Methods for Coated Fabrics Used in Oil Spill Control and Storage”, section 4.8 “Seam Strength”, Annual Book of ASTM Standards Vol. 11.04.

Results:

Test data are summarized in the following table:

Binding Technique	Seam Type	Fabric or Seam Failure	Force at Breaking (lbs)
1 row stitches	Butt	seam	558.0
2 row stitches	Butt	seam	573.0
3 row stitches	Butt	seam	617.0
1 row 0.5" staples	Butt	seam	347.7
2 row 0.5" staples	Butt	seam	443.4
1 row std. staples	Butt	seam	63.5
2 row std. staples	Butt	seam	82.0
1 row stitches	Overlap	seam	516.6
2 row stitches	Overlap	seam	1028.3
3 row stitches	Overlap	seam	1199.2
1 row 0.5" staples	Overlap	seam	1534.0
2 row 0.5" staples	Overlap	fabric	2676.9
1 row std. staples	Overlap	seam	195.3
2 row std. staples	Overlap	seam	415.0

These test results indicate that Overlap seams are superior to Butt seams, there is no strength advantage to stitching overlap seams compared to use of 0.5 inch staples, but standard office staples should be avoided. Long term robustness or degradation was not considered since the purpose of these tests was to evaluate staples as an alternative method for fabricating test prototypes only.

APPENDIX II: SLICK PROFILE ANALYSIS MATLAB PROGRAMS

Profile Analysis

Oil.m: This matlab program was developed to analyze the digital video recordings.

```
clear
clc
pth=input('What directory is the video in? (ie d:\oil3\) ','s');
fname=input('What is the name of the file? ','s');
f=input('How many frames should be analyzed? ');
fps=input('What is the sampling rate (Frames/sec)? ');
diam=input('What is the diameter of the calibration circle? ');
units=input('What are the units of the diameter? ','s');




%Calibration
cname=input('What is the name of the calibration file? ','s');
cfile=[pth,cname,'0001.bmp'];
Intensity=input('At what intensity should the calibration begin (0-256)? ');
dummy1=0;
while dummy1~='y',
	pix=0;
	error=0;
	if dummy1==0
		Zoom='Area of Calibration Circle';
		Zoom
		[A,map]=bmpread(cfile);
		imshow(A,map);
		[C,rect]=imcrop;
		A=C;
	else
		C=A;
		end
	j=1;
	while j<=rect(1,3),
		i=1;
		p=0;
		while i<=rect(1,4),
			if C(i,j)<=Intensity
```

```
                    p=p+1;
                    C(i,j)=0;
                    end
                i=i+1;
                end
            if p>pix
                pix=p;
                col=j;
                end
            j=j+1;
            end
if pix==0
        error=1;
else
        caly=diam/pix;
        end
pix=0;
i=1;
while i<=rect(1,4),
        j=1;
        p=0;
        while j<=rect(1,3),
            if C(i,j)<=Intensity
                p=p+1;
                C(i,j)=0;
                end
            j=j+1;
            end
        if p>pix
            pix=p;
            row=i;
            end
        i=i+1;
        end
if pix==0
        error=1;
else
        calx=diam/pix;
        end
if error==0
        C(row,1)=256;
        C(1,col)=256;
else
        error='No pixels are that low an intensity.  Try a higher number.';
        error
```

```
            end
        imshow(C,map);
        drawnow;
        dummy1=input('Is this calibration correct (y/n)?  ','s');
        if dummy1=='y' | isempty(dummy1)
            break
            end
        Intensity
        Intensity=input('What is the new intensity value (0-256)?  ');
        end
cal(1)=calx;
cal(2)=caly;




%Area of Interest

Message='You will be prompted to pick an area of interest';
Message
efile=[pth,fname,'0001.bmp'];
[A,map]=bmpread(efile);

dummy1=input('Do you want to zoom to the area of interest? (y/n)  ','s');
if dummy1=='y'
        dummy1='n';
        imshow(A,map);
        while dummy1~='y',
            imzoom on;
            dummy1=input('Are you done zooming? (y/n)  ','s');
            end
        imzoom off;
        Message='Pick the Area of Interest';
        Message
        dummy1='n';
        while dummy1~='y',
            [C,rect]=imcrop;
            imshow(C,map);
            drawnow;
            dummy1=input('Is this area of interest satisfactory? (y/n)  ','s');
            if dummy1~='y'
                break;
                end
```

```
            end

else
        Message='Pick the Area of Interest';
        Message
        dummy1='n';
        while dummy1~='y',
                imshow(A,map);
                [C,rect]=imcrop;
                imshow(C,map);
                drawnow;
                dummy1=input('Is this area of interest satisfactory? (y/n)  ','s');
                end
        end


%Intensity Calibration

Message='You will need to calibrate the system to find the oil.'
Message
Intensity=input('At what intensity should the calibration begin (0-256)?  ');
dummy1=1;
D=C;
subplot(2,1,1), imshow(D,map);
while dummy1 ~= 'y',
        j=1;
        while j<=rect(1,3),
                i=1;
                while i<=rect(1,4),
                        if C(i,j)<=Intensity
                                C(i,j)=256;
                                end
                        i=i+1;
                        end
                j=j+1;
                end
        subplot(2,1,2), imshow(C,map);
        dummy1 = input('Is this calibration satisfactory? (y/n)  ','s');
        if dummy1 ~= 'y'
                C=D;
                Intensity=input('What should the new intensity be? (0-256)  ');
                end
        end
subplot(1,1,1)
```

```
%Frame Analysis

k=1;
while k<=f,
	if k<10
		file=[pth,fname,'000',int2str(k),'.bmp'];
	elseif k>9 & k<100
		file=[pth,fname,'00',int2str(k),'.bmp'];
	elseif k>99 & k<1000
		file=[pth,fname,'0',int2str(k),'.bmp'];
	elseif k>999 & k<10000
		file=[pth,fname,int2str(k),'.bmp'];
	else
		Error='Do you know how long that would take?'
		return
		end
	[A,map]=bmpread(file);



	j=rect(1,1);
	count=1;
	while j<=rect(1,1)+rect(1,3),
		B(k,count)=0;
		i=rect(1,2);
		while i<=rect(1,2)+rect(1,4),
			if A(i,j)<=Intensity
				A(i,j)=256;
				B(k,count)=B(k,count)+1;
				end
			i=i+1;
			end
		j=j+1;
		count=count+1;
		end
	k
	imshow(A,map);
	drawnow;
	k=k+1;
```

```
        end



for k=1:f
        for j=1:rect(1,3)+1
                B(k,j)=B(k,j)*cal(2);
                end
        end

figure(1);
whitebg(1,'k');
[m,n]=size(B);
surfl((1:n)*calx,(0:m-1)/fps,B);
shading interp;
xaxis=['Horizontal Distance (',units,')'];
xlabel(xaxis);
ylabel('Time (sec)');
zaxis=['Oil Thickness (',units,')'];
zlabel(zaxis);

figure(2);
whitebg(2,'w');
plot(calx*(1:n),B,'k');
title('Wave Evolution');
xaxis=['Horizontal Distance (',units,')'];
xlabel(xaxis);
yaxis=['Oil Thickness (',units,')'];
ylabel(zaxis);
[maxy,maxx]=max(B');
for i=1:m,
        label=['Time =',num2str((i-1)/fps)];
        text(maxx(i)*calx,maxy(i),label);
        end
axis('ij');
```

Curve Fitting

```
% This m-file is developed to perform a curve fitting to a given
% wave form.

y=input('Enter the name of the vector for the points along the x-axis ');

calx=input('Enter the cal. factor on the x-direction ');

[m,n]=size(y);
x=calx*(1:n);

y=(-1)*y;
plot(x,y);

xi=0:2*calx:calx*length(x);
yi=spline(x,y,xi);
plot(x,y,'y:',xi,yi,'r')
xlabel('Slick length (cm)'); ylabel('wave height (cm)');
title('Dimensional 2D Oil Slick Profile');

q=n;

q=input('Is this curve fitting satisfactory (y/n) ','s');
        while q~='y'
        doom=input('Enter a calibration factor (1-10) ' );
        xi=0:doom*0.1:calx*length(x);
        yi=spline(x,y,xi);
        plot(x,y,'y:',xi,yi,'r')
        xlabel('Slick length (cm)'); ylabel('wave height (cm)');
        title('Dimensional 2D Oil Slick Profile');
        q=input('Is this curve fitting satisfactory (y/n) ','s');
                if q=='y'
                Message='Thank you'
                break
                end
        end
Pi(1,:)=xi;
Pi(2,:)=yi;

P(1,:)=x;
P(2,:)=y;
```